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PUBLICATIONS OF THE GEOLOGICAL SOCIETY OF AMERICA

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The Society issues annually, in four quarterly parts, a single serial octavo publication entitled Bulletin of the Geological Society of America, the edition being 850 copies. A small supply of authors' separates of the longer articles is kept for sale by the Secretary at the prices quoted in each volume.

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The price of the index to volumes 1-10 is $2.25; to volumes 11-20, $3.50, and to volumes 21-30, $4.00; carriage extra. No reduction is made to dealers. Orders should be addressed to the Secretary, whose address is care of Columbia University, New York, N. Y., and drafts and money orders should be made payable to *The Geological Society of America*.

Description of the Published Volumes

Volumes.	Pages.	Plates.	Figures.
Vol. 1, 1889	593 + xii	13	51
Vol. 2, 1890	622 + xiv	23	63
Vol. 3, 1891	541 + xi	17	72
Vol. 4, 1892	458 + xi	10	55
Vol. 5, 1893	655 + xii	21	43
Vol. 6, 1894	528 + x	27	40
Vol. 7, 1895	558 + x	24	61
Vol. 8, 1896	446 + x	51	29
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Vol. 21, 1909	823 + xvi	54	109
Vol. 22, 1910	747 + xii	31	66
Vol. 23, 1911	758 + xvi	43	44
Vol. 24, 1912	737 + xviii	36	60
Vol. 25, 1913	802 + xviii	28	47
Vol. 26, 1914	504 + xxi	27	41
Vol. 27, 1915	739 + xviii	30	55
Vol. 28, 1916	1005 + xxii	48	102
Vol. 29, 1917	679 + xix	22	67
Vol. 30, 1918	644 + xiii	15	40
Index to volumes 21–30	325	..	..
Vol. 31, 1919	450 + xviii	14	7
Vol. 32, 1920	488 + xviii	12	60
Vol. 33, 1921	862 + xxi	5	115
Vol. 34, 1922	748 + xx	12	125
Vol. 35, 1923	896 + xxii	36	95
Vol. 36, 1924	707 + xx	10	118

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	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Number 1	1–278	1–7	....	$3.00	$4.50
Number 2	279–434	8–10	23	1.65	2.50
Number 3	435-582	....	38	1.50	2.25
Number 4*	583-707	....	57	1.25	1.90

REPRINTS FROM VOLUME 36

REPRINTS.	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Proceedings of the Thirty-seventh Annual Meeting of the Geological Society of America, held at Ithaca, New York, Monday-Wednesday, December 29-31, 1924. C. P. BERKEY, *Secretary*.	1–198	1–7	....	$2.20	$3.30
Proceedings of the Twenty-third Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Stanford University, California, May 2 and 3, 1924. J. P. BUWALDA, *Secretary*	199–210	....	....	.10	.15
Proceedings of the Sixteenth Annual Meeting of the Paleontological Society, held at Ithaca, New York, December 29-31, 1924. R. S. BASSLER, *Secretary*†	211–240	....	....	.30	.45
Proceedings of the Fifth Annual Meeting of the Mineralogical Society of America, held at Cornell University, Ithaca, New York, December 31, 1924. F. R. VAN HORN, *Secretary*	241–246	....	....	.10	.15
Metasomatism. WALDEMAR LINDGREN	247–262	....	....	.15	.25
On correlation. E. W. BERRY†	263–278	....	....	.10	.25
Marine and terrestrial conglomerates. JOSEPH BARRELL	279–342	....	6	.65	.95
Significance of Taconic orogeny. C. SCHUCHERT	343–350	....	....	.10	.15
Coutchiching problem. F. F. GROUT	351–364	....	9	.15	.25
Erosion in San Juan Canyon, Utah. H. D. MISER	365–378	8–9	2	.20	.30
Structural geology of the mid-continent region; a field for research. S. POWERS	379–392	....	....	.15	.25
Relation of texture and composition of clays. F. F. GROUT	393–416	....	2	.25	.40
Glacial Kankakee torrent in northwestern Illinois. G. E. EKBLAW and L. F. ATHY	417–428	....	4	.10	.15

* Preliminary pages and index are distributed with number 4.

† Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

Reprints.	Pages.	Plates.	Figures.	Price to Fellows.	Price to Public.
Buried Indian workshop with remains of an extinct mammal. W. A. Parks†	429–434	10	....	$0.10	$0.15
Cretaceous and tertiary formations of the Wasatch Plateau, Utah. E. M. Spieker and J. B Reeside	435–454	....	3	.20	.30
Chagrin formation of Ohio. G. H. Chadwick	455–464	....	2	.10	.15
Active thrust-faults in San Benito County, California. P. F. Kerr and H. G. Schenck	465–494	....	13	.30	.45
Erosional cycles in the Front Range of Colorado, and their correlation. H. P. Little	495–512	....	11	.20	.30
Remarkable Adirondack glacial lake. W. J. Miller	513–520	....	1	.10	.15
Eustatic bench of islands of the North Pacific. C. K. Wentworth and H S. Palmer	521–544	....	14	.25	.40
Basic dike injections in magmatic vein sequences. J. E. Spurr	545–582	....	4	.40	.60
Dentition of Artiodactyls. F. B. Loomis†	583–604	....	20	.20	.30
Mechanics of crocodile vertebrae. E. L. Troxell†	605–614	....	6	.10	.15
Mineralization of the Platteville-Decorah contact zone in the Twin City region. C. R. Stauffer	615–622	....	....	.10	.15
Keystone faults. W. O. Crosby and I. B. Crosby	623–640	....	1	.20	.30
Physiography of the California coast ranges. Robin Willis	641–678	....	23	.40	.60
Primary structure of granite massives. Robert Balk	679–696	....	7	.20	.30

† Under the brochure heading is printed Proceedings of the Paleontological Society.

Irregular Publications

In the interest of exact bibliography, the Society takes cognizance of all publications issued wholly or in part under its auspices. Each author of a memoir receives 40 copies without cost, and is permitted to order any additional number at a slight advance on cost of paper and presswork; and these reprints are identical with those of the editions issued and distributed by the Society; but the cover bears only the title of the paper, the author's name, and the statement [Reprinted from the Bulletin of the Geological Society of America, vol. —, pp. —, pl. — (Date)]. Contributors to the Proceedings and "Abstracts of Papers" are also authorized to order any number of separate copies of their papers at a slight advance on cost of paper and presswork; but such separates are bibliographically distinct from the reprints issued by the Society.

Regular Editions

Pages 247–262,		150	copies,	March	30, 1925.
" 263–278,*†		225	"	"	30, 1925.
" 279–342,		275	"	June	30, 1925.
" 343–350,		275	"	"	30, 1925.
" 351–364,		110	"	"	30, 1925.
" 365–378,	plates 8–9,	110	"	"	30, 1925.
" 379–392,		250	"	"	30, 1925.
" 393–416,		50	"	"	30, 1925.
" 417–428,		350	"	"	30, 1925.
" 429–434,	plate 10,	245	"	"	30, 1925.
" 435–454,		90	"	September	30, 1925.
" 455–464,		150	"	"	30, 1925.
" 465–494,		250	"	"	30, 1925.
" 495–512,		50	"	"	30, 1925.
" 513–520,		75	"	"	30, 1925.
" 521–544,		250	"	"	30, 1925.
" 545–582,		50	"	"	30, 1925.
" 583–604,*†		325	"	December	30, 1925.
" 605–614,*†		375	"	"	30, 1925.
" 615–622,		100	"	"	30, 1925.
" 623–640,		110	"	"	30, 1925.
" 641–678,		100	"	"	30, 1925
" 679–696,		50	"	"	30, 1925.

Special Editions‡

Pages 15– 44,	plate 1,	450	copies,	March	30, 1925.
" 45– 84,	" 2,	50	"	"	30, 1925.
" 85–100,	" 3,	250	"	"	30, 1925.
" 100–115,	" 4,	250	"	"	30, 1925.
" 116–128,	" 5,	250	"	"	30, 1925.
" 183–198,		200	"	"	30, 1925.
" 199–210,		50	"	"	30, 1925.
" 211–240,*†		175	"	"	30, 1925.
" 241–246,		50	"	"	30, 1925.

* Bearing on the cover
PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.
[Reprinted from the Bulletin of the Geological Society of America, vol. ——, pp. ——, pls. ——, (Date).]

† Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

‡ Bearing imprint [From BULL. GEOL. SOC. AM., Vol. 36, 1924]

CORRECTIONS AND INSERTIONS

Contributors to volume 36 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

Page 358, line 12 from top *for* "Anglomian" *read* Algomian

" 403, and 414, *transpose* cuts 1 and 2, the numbers and legends remaining as given

" 421, line 1 at bottom of page, *for* "vidence" *read* evidence

" 433, plate 10, line 7 from bottom, *for* "All figures × 2.4" *read* All figures × 1.4

" " " " line 3 from bottom, for "Figare 3, Third molar" *read* Figure 3, First molar

" 434, At bottom of page *add* the following footnote: In 1925 the bog was drained and examined to a depth of 17 feet. The results were unsatisfactory, as little additional material was obtained. The remains are confined to the immediate vicinity of the spring and not scattered near the floor of the basin, as had been expected

" 457, line 27 from top, *for* "Upper standstone" *read* Upper sandstone

" 462, line 22 from top, *for* "This" *read* That

" 513, line 6 from top, *transfer* [5]Published by permission of the State Geologist of New York" to the bottom of the page

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 36, PP. 1-198, PLS. 1-7 MARCH 30, 1925

PROCEEDINGS OF THE THIRTY-SEVENTH ANNUAL MEETING OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT ITHACA, NEW YORK, MONDAY–WEDNESDAY, DECEMBER 29–31, 1924.

CHARLES P. BERKEY, *Secretary*

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Session of Monday Morning, December 29, 1924

The thirty-seventh annual meeting of the Geological Society of America was called to order in the Auditorium of Baker Chemical Laboratory, Cornell University, Ithaca, New York, at 9:10 a. m., by Vice-President William A. Parks. Brief introductory remarks were made by the presiding officer, who called attention to the fact that, although the Society was organized at Cornell University in 1888, this meeting marks the first return since that time.

REPORT OF THE COUNCIL

The report of the Council was presented by Secretary Berkey, as follows:

To the Geological Society of America, in thirty-seventh annual meeting assembled:

The regular annual meeting of the Council was held at Washington, D. C., in connection with the meeting of the Society, December 27-29, 1923. Special meetings were held in New York City on April 18 and October 11, 1924.

The details of administration for the thirty-sixth year of the existence of the Society are given in the following reports of the officers:

President's Report

To the Council of the Geological Society of America:

The President's report for the year ending November 30, 1924, is as follows:

The policies entered upon by the preceding administration, including the requirement of an abstract for each title offered for the program of the annual meeting, and the organization of a program plan, have been continued, and the results appear to have justified the additional attention given to these matters. This year every title submitted has been accompanied by a reasonably suitable abstract, and the program has taken on a form that avoids serious conflict of sessions. The list of foreign correspondents is increased conservatively and the committee is working on a policy of systematic and carefully weighed expansion. The project proposed last year, of establishing a geological abstract journal, has not materialized, due to lack of financial support.

The principal activities of the Council outside of the regular administrative work of the different responsible officers have been carried on through the following committees:

Membership Committee: Lewis G. Westgate, Chairman; W. H. Twenhofel, David White.

Program Committee: Waldemar Lindgren, Chairman; Charles P. Berkey, Fred. E. Wright, Alan M. Bateman, R. S. Bassler, Frank R. Van Horn, Edward W. Berry.

Committee on Foreign Correspondents: James F. Kemp, Chairman; Arthur P. Coleman, John M. Clarke, D. W. Johnson, Henry S. Washington.

Committee on Exchanges: Charles Schuchert, Chairman; Edmund Otis Hovey, Henry S. Washington. (After the death of Doctor Hovey, Edward W. Berry was appointed to this committee.)

Finance Committee: Edmund Otis Hovey, Joseph Stanley-Brown, R. A. F. Penrose, Jr. (After the death of Doctor Hovey, Fred. E. Wright was appointed to this committee.)

Committee on Publication: James F. Kemp, Edmund Otis Hovey, Joseph Stanley-Brown, Charles P. Berkey, Edward B. Mathews. (After the death of Doctor Hovey, Charles Schuchert was appointed to this committee.)

Local Committee for the Ithaca Meeting: Heinrich Ries, Chairman; H. F. Vieweg, C. M. Nevin, O. D. Von Engeln, R. E. Rettger.

During the year several important appointments have been made of representatives and delegates to scientific meetings and to represent the Society at public functions and celebrations, as follows:

The Joseph A. Holmes Safety Association: Delegate, John J. Rutledge.
The Society of Economic Geologists: Delegate, Edmund Otis Hovey. (After the death of Doctor Hovey, Adolph Knopf was appointed.)
Third Pan-American Scientific Congress: Delegate, Donald H. McLaughlin.
International Mathematical Congress: Delegates, William A. Parks, Frank D. Adams.
Franklin Institute Centenary: Representative, R. A. F. Penrose, Jr.
Rensselaer Polytechnic Institute Centenary: Representative, John M. Clarke.
Dedication of new buildings of the School of Medicine, Western Reserve University: Representative, Frank R. Van Horn.
Inauguration of Robert Ernest Vinson as President of Western Reserve University: Representative, Frank R. Van Horn.
Advisory Council of the Federated American Engineering Societies: Representative, David White.

Respectfully submitted, WALDEMAR LINDGREN,
President.

Secretary's Report

To the Council of the Geological Society of America:

The Secretary's annual report for the year ending November 30, 1924, is as follows:

Meetings.—The proceedings of the annual meeting of the Society, held at Washington, D. C., December 27-29, 1923, have been recorded in volume 35, pages 1-160 of the Bulletin. Those of the Cordilleran Section, pages 161-168 of the Bulletin; of the Paleontological Society, pages 169-200; of the Mineralogical Society of America, pages 201-206, of the same volume.

Membership.—During the last year the Society has lost by death three Correspondents—Giovanni Capellini, Sir Archibald Geikie, and Sir Jethro J. H. Teall—and five Fellows—Alfred H. Brooks, Edmund Otis Hovey, John J. Stevenson, Thomas L. Watson, and Robert S. Woodward. The names of the 20 candidates elected at the Washington meeting have been added to the printed list. There have been no names dropped from the list for non-payment of dues. There have been two resignations for the year. The present enrollment of the Society is 498. Seventeen candidates for Fellowship are before the Society for election, three for correspondentship, and several applications are under consideration by the Council.

Distribution of the Bulletin.—During the past year there have been sent out to domestic subscribers 149 copies and to foreign subscribers 50 copies of volume 35 of the Bulletin, 32 going to new subscribers. This shows an increase in subscriptions over last year of 26 copies. Six volumes have been distributed gratis, as follows: Library of Congress, American Museum of Natural History, the Government Geological Surveys of the United States, Canada, Mexico, and the Bureau of Science, Manila, Philippine Islands. Fifty-nine copies have been sent to our foreign exchange list. The receipts of this office, including subscriptions to and sales of the Bulletin and separate brochures therefrom, are summarized as follows:

Detailed Financial Statement of the Secretary's Office

RECEIPTS

Regular subscriptions	$1,954.00
Irregular sales	1,501.24
Geological Magazine	132.31
Post and express refunds	83.63
Authors' separates and corrections	271.18

Exchange added to checks	1.35	
Programs	33.75	
		$3,977.46
Sent to Treasurer		3,263.59
Balance on hand		$713.87

DISBURSEMENTS

On account of administration:		
Expenses, Washington meeting:		
Printing	$264.50	
Lantern and operator	40.00	
		$304.50
Printing for 1924		139.00
Cordilleran Section:		
Printing	$31.75	
Dues, American Association for the Advancement of Science, Pacific Division	10.00	
		41.75
Clerical help (1923 account)		200.00
Clerical help (1924 account)		400.00
Repairing typewriter		10.00
Engraving Correspondents' certificates		4.20
Binding Bulletin (6 volumes)		25.00
Postage		28.22
Exchange on checks		6.00
Telegrams and telephone calls		10.02
Miscellaneous supplies		7.74
Cost of shipping sets of Bulletin to Australia and Sweden		34.25
Total		$1,210.68

ON ACCOUNT OF BULLETIN

150 copies Constitution and By-Laws		$4.00
300 copies Lists of Officers and Fellows		7.50
Office expenses:		
Carfare	$1.20	
Telegrams	6.46	
Postage and express charges	75.80	
Notary fees	1.50	
Addressograph plates	2.72	
Miscellaneous supplies	10.03	
		97.71
Total		$109.21

Respectfully submitted,

CHARLES P. BERKEY,
Secretary.

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his report for the year ending November 30, 1924.

The membership of the Society on December 1, 1923, consisted of 379 paying annual dues, 93 Life Members, and 11 Correspondents. Twenty new members qualified during the year. Three Life Members, 3 Correspondents, and 2 Annual Members have died during the year, and 2 Annual Members have resigned. One Annual Member was elected Correspondent. As the books close, the membership consists of 90 Life Members, 394 Annual Members, and 14 Correspondents, making a total of 498.

The fees receivable at the beginning and close of the year are as follows:

	Receivable Dec. 1, 1923	Collected to Nov. 29, 1924	Due Dec. 1, 1924	
Fees of delinquents (1922, 1923)	$210.00	$80.00	$230.00	
Annual fees (1924)	3,970.00	3,770.00	70.00	
				$300.00
Advanced payments (1925)	43.40	43.40		
Initiation fees (20)	200.00	200.00		
				4,093.40
	4,423.40			
Less adjustments	30.00*			
	$4,393.40			$4,393.40

RECEIPTS

Cash in bank December 1, 1923		$3,285.65
Annual dues:		
From delinquents	$80.00	
For 1924	3,770.00	
For 1925	43.40	
		3,893.40
Initiation fees (20) at $10		200.00
Interest:		
On investments	$1,540.00	
On deposits	150.04	
		1,690.04
Foreign exchange added to checks		.16
Redemption of bonds:		
Braden Copper Mining Co., called at 105.	$1,050.00	
U. S. Steel Corporation, called at 110	1,100.00	
		2,150.00

* Includes $10 loss by death, $20 paid prior to 1924.

Case Library		900.00	
Received from Secretary:			
Exchange added to checks	$1.35		
Sales of publications	2,834.84		
Geological Magazine	132.31		
Postage and express refunds	79.32		
Authors' separates	173.35		
Miscellaneous	42.42		
		3,263.59	
			$15,382.84

DISBURSEMENTS

Secretary's office:			
Administration	$1,210.68		
Bulletin	109.21		
Portrait	5.00		
Geological Magazine	194.74		
Allowance	1,000.00		
		$2,519.63	
Treasurer's office:			
Expenses	$95.50		
Clerk	150.00		
		245.50	
Publication of Bulletin:			
Printing	$3,403.19		
Engraving	563.11		
Editor's allowance	250.00		
		4,216.30	
Mineralogical Society of America		93.00	
Investments:			
2 Baltimore & Ohio bonds	$1,998.00		
2 Commonwealth Edison bonds	1,983.00		
		3,981.00	
Accrued interest in coupons		55.83	
Purchase of rare Bulletins		712.02	
			$11,823.28
Balance in Baltimore Trust Company			3,559.56
			$15,382.84

Respectfully submitted, EDWARD B. MATHEWS,
Treasurer.

EDITOR'S REPORT

To the Council of the Geological Society of America:

The following tables cover statistical data for the thirty-five volumes thus far issued:

ANALYSIS OF COSTS OF PUBLICATION

Cost.	Average—Vols. 1-30.	Vol. 31.	Vol. 32.	Vol. 33.	Vol. 34	Vol. 35
	pp. 737. pls. 31.	pp. 468. pls. 14.	pp. 506. pls. 12	pp. 862. pls. 5.	pp. 778. pls. 20.	pp. 896 pls 36
Letter press	$1,776.16	$1,541.45	$1,883.18	$3,006.32	$2,572.34	$4 048.05
Illustrations	433.34	131.94	272.44	616.01	499.36	768.86
Paper	428.12	266.64	792.00	686.81	424.87	570.62
Total	$2,566.03	$1,940.03	$2.947.62	$4,309.14	$3,496.57	$5,387.53
Average per page	$3.51	$4.15	$5.83	$5.00	$4.62	$5.84

CLASSIFICATION OF SUBJECT-MATTER

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geology.	Official matter.	Memorials.	Unclassified.	Total.
	Number of Pages.											
1....	116	137	92	18	83	44	47	...	60	4	4	593+xii
2....	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3....	56	41	44	41	32	158	104	...	61	15	1	541+xii
4....	25	134	38	74	52	52	14	...	47	32	2	458+xii
5....	138	135	70	54	28	51	107	...	71	14	9	665+xii
6....	50	111	75	39	71	99	1	...	63	25	4	538+x
7....	38	77	105	53	40	21	123	4	66	28	13	558+x
8....	34	50	98	5	43	67	58	14	79	8	...	446+x
9....	2	102	138	...	44	28	64	16	64	12	...	460+x
10....	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11....	65	110	21	10	54	31	188	7	71	60	46	651+xii
12....	199	39	55	53	24	98	5	5	70	2	...	538+xi
13....	125	17	13	24	28	116	42	4	165	32	29	583+xii
14....	48	47	48	59	183	118	22	1	80	14	1	609+xi
15....	26	124	3	94	36	267	...	...	77	17	3	636+x
16....	64	111	78	30	102	141	19	...	67	22	15	636+xiii
17....	49	161	41	84	47	294	27	...	71	9	2	785+xiv
18....	16	164	141	5	29	246	5	...	68	40	3	717+xii
19....	106	108	29	66	30	155	32	...	56	15	20	617+x
20....	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21....	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22....	23	54	28	28	23	403	74	...	63	49	1	747+xii
23....	75	52	126	108	19	145	134	...	66	32	1	758+xvi
24....	18	57	96	57	49	160	106	23	133	53	3	737+xviii
25....	34	211	54	32	156	9	175	...	108	9	22	802+xviii
26....	...	72	23	11	56	90	148	...	54	44	6	504+xxi
27....	1	59	125	31	146	20	271	2	73	24	5	739+xviii
28....	25	273	70	69	78	200	55	39	94	110	14	1005+xxii
29....	3	107	62	15	127	169	64	...	73	57	21	679+xix
30....	160	3	41	9	5	36	205	16	73	59	50	644+xiii
31....	1	80	19	4	13	45	22	21	69	97	79	450+xviii
32....	73	47	7	27	63	51	77	17	105	2	37	488+xviii
33....	39	166	160	47	97	107	101	3	91	41	31	862+xxi
34....	20	256	73	2	39	149	48	...	89	38	64	778+xx
35....	44	72	17	83	70	140	269	...	76	46	79	896+xxii

Respectfully submitted,

JOSEPH STANLEY-BROWN, *Editor.*

The foregoing report is respectfully submitted.

THE COUNCIL.

December 29, 1924.

ELECTION OF AUDITING COMMITTEE

The printed report of the Council was distributed to all members in attendance. Since the report of the Council contains the Treasurer's report, it was laid on the table pending examination of the Treasurer's accounts by an auditing committee named from the floor, consisting of Eliot Blackwelder, chairman, Joseph T. Singewald, Jr., and Adolph Knopf.

ELECTION OF OFFICERS, REPRESENTATIVES, CORRESPONDENTS, AND FELLOWS

The Secretary then read the result of the ballot for officers of the Society for the year 1925, and representatives to the National Research Council, and of the ballot for Correspondents and Fellows. The following were declared elected:

President:

WILLIAM B. SCOTT, Princeton, New Jersey

First Vice-President:

REGINALD W. BROCK, Vancouver, British Columbia

Second Vice-President:

MARIUS R. CAMPBELL, Washington, D. C.

Vice-President to represent the Paleontological Society:

R. S. LULL, New Haven, Connecticut

Vice-President to represent the Mineralogical Society:

ARTHUR S. EAKLE, Berkeley, California

Secretary:

CHARLES P. BERKEY, New York City

Treasurer:

EDWARD B. MATHEWS, Baltimore, Maryland

Editor:

JOSEPH STANLEY-BROWN, New York City

Councilors (1923-1925) *to fill unexpired term:*

CHARLES CAMSELL, Ottawa, Canada
JOHN A. BOWNOCKER, Columbus, Ohio

Councilors (1924-1926):

U. S. GRANT, Chicago, Illinois
FLORENCE BASCOM, Bryn Mawr, Pennsylvania

Representatives on the National Research Council (*July* 1, 1925, *to June* 30, 1928):

CLARENCE N. FENNER, Washington, D. C.
L. C. GRATON, Cambridge, Massachusetts

CORRESPONDENTS

ALFRED HARKER, Cambridge, England, Lecturer in Petrology, Saint John's College, Cambridge University.

ARTHUR WILLIAM ROGERS, Cape Town, South Africa, Director, Geological Survey, Cape Province.

CARLO DE STEFANI, Florence, Italy, Professor of Geology and Physical Geography, Royal University.

FELLOWS

MAX WAITE BALL, E. M., LL. M., President, Marine Oil Company, Ute Petroleum Company, Western Pipe Line Company, Denver, Colorado.

ISAIAH BOWMAN, B. S., Ph. D., Director, American Geographical Society, New York City.

EDWARD DE COURCY CLARKE, M. A., Lecturer in Charge of Geology, University of Western Australia, Perth, Western Australia.

ROY JED COLONY, B. Ch., A. M., Assistant Professor of Geology, Columbia University, New York City.

LEO ARTHUR COTTON, M. A., D. Sc., Assistant Professor of Geology, University of Sydney, Sydney, Australia.

CHARLES ELIJAH DECKER, A. B., A. M., Ph. D., Associate Professor of Geology, University of Oklahoma, Norman, Oklahoma.

CHARLES REINHARD FETTKE, B. S., M. A., Ph. D., Associate Professor of Geology and Mineralogy, Carnegie Institute of Technology, Pittsburgh, Pennsylvania.

CHARLES WHITNEY GILMORE, B. S., Curator of Vertebrate Paleontology, United States National Museum, Washington, D. C.

THOMAS MCDOUGALL HILLS, Ph. B., Professor of Geology, Vassar College, Poughkeepsie, New York.

ARMIN KOHL LOBECK, A. B., A. M., Ph. D., Associate Professor of Physiography, University of Wisconsin, Madison, Wisconsin.

FRANK REEVES, A. B., Ph. D., Geologist, United States Geological Survey, Washington, D. C.

EDWARD SAMPSON, C. E., M. Sc., D. Sc., Geologist, United States Geological Survey, Washington, D. C.

JULIAN DUCKER SEARS, A. B., Ph. D., Geologist, United States Geological Survey, Washington, D. C.

EDMUND MAUTE SPIEKER, A. B., Ph. D., Geologist, United States Geological Survey, Washington, D. C.

WILLIAM TAYLOR THOM, JR., S. B., Ph. D., Geologist in Charge Geology of Fuels, United States Geological Survey, Washington, D. C.

LEONARD KEITH WARD, B. A., B. E., Government Geologist of South Australia, Adelaide, South Australia.

WALTER GEORGE WOOLNOUGH, B. S., D. Sc., Consulting Geologist to Messrs. Brunner, Mond & Co., Ltd., England, Killara, New South Wales.

NECROLOGY

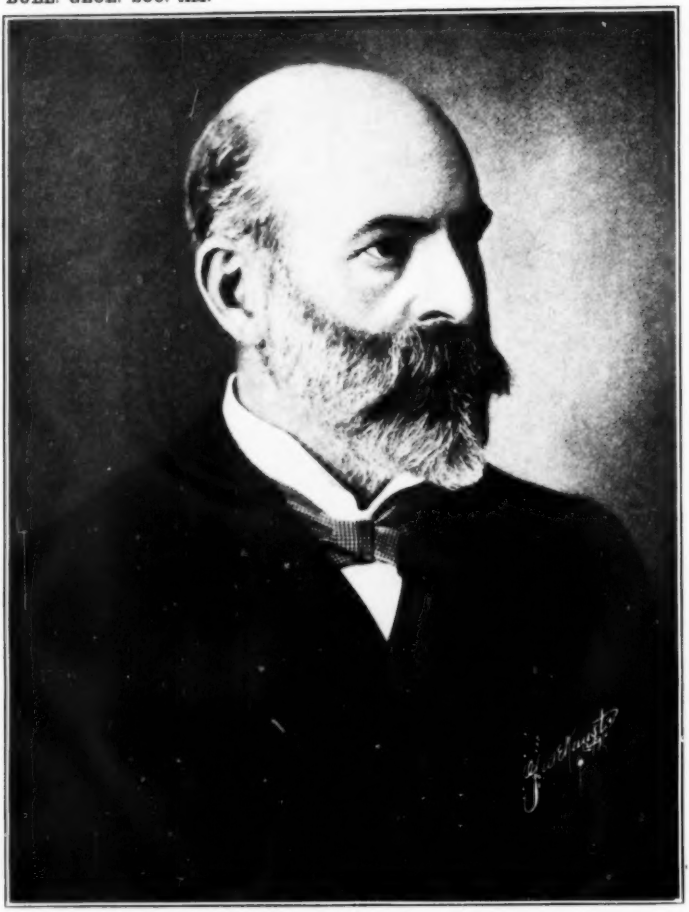
The Secretary announced the deaths during the year of five Fellows and three Correspondents. Brief oral tributes were then called for and responded to as follows:

Alfred Hulse Brooks, by George Otis Smith.
Edmund Otis Hovey, by James F. Kemp.
John J. Stevenson, by I. C. White.
Thomas L. Watson, by Heinrich Ries.
Robert S. Woodward, by F. E Wright.
Giovanni Capellini, by Henry S. Washington.

The tribute prepared by John M. Clarke for Sir Archibald Geikie was read by Charles P. Berkey, and the one prepared by Whitman Cross for Sir J. J. H. Teall was read by David White.

MEMORIALS

The written memorials are printed in the Proceedings. In addition to those already listed, the memorials of John Casper Branner, by R. A. F. Penrose, Jr., and of Raphael Pumpelly, by Bailey Willis, held over from a previous year, are included.



J. C. Branner

MEMORIAL TO JOHN CASPER BRANNER[1]

BY R. A. F. PENROSE, JR.

John Casper Branner was born at the town of New Market, Jefferson County, Tennessee, on July 4, 1850, and was a son of Michael T. Branner and Elsie Baker Branner. His family were among the early settlers of the Shenandoah Valley of Virginia in colonial days, and in 1760 his ancestor Casper Branner received a grant of land there from Lord Fairfax, who had been given large estates in Virginia by Charles II.

About the year 1799 Doctor Branner's great-grandfather, Michael Branner, moved to Jefferson County, Tennessee, and became the progenitor of the Tennessee branch of the family, while his brother, John Branner, remained in the Shenandoah Valley and became the head of the Virginia Branners. Both branches have spread widely through many parts of the United States. Strong, active, and earnest people have been characteristic of the family, and many of them have occupied high positions in the communities in which they lived.

In the childhood of Doctor Branner the neighborhood was sparsely settled and books and schools were not numerous. His early education, therefore, was confined largely to such local schools as were available and to the reading of such books as could be obtained. He was of an inquiring disposition, however, and in the scarcity of books he early developed a deep interest in the natural features of the country surrounding him. He rapidly became familiar with the character of the rocks and of the animals and flowers that occurred in the neighborhood. This early bringing up in close contact with nature, followed later by an education in institutions of high learning, doubtless served to develop that remarkable originality and initiative which distinguished him in later life and which produced a man who became eminent among the scientists of his generation.

In 1866 Doctor Branner went to Maryville College, near Knoxville, Tennessee, where he remained for about two years. He was then eighteen years of age, and the new institution known as Cornell University had lately been established at Ithaca, New York. He was attracted by the opportunities for study there and entered the university in 1870.

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[1] Manuscript received by the Secretary of the Society January 8, 1925.

The writer desires to express his sincere appreciation for the information given him by Mrs. J. C. Branner in the preparation of this memoir. Such assistance has always been willingly granted and has greatly helped him in his description of the life-work of Doctor Branner.

At Cornell Doctor Branner took up mostly scientific courses, particularly in geology, botany, zoology, and other branches of natural science. Here also he had the good fortune to meet Prof. Louis Agassiz and Doctor Charles F. Hartt, the latter then professor of geology at Cornell. Doctor Hartt had made several trips to Brazil in previous years and had published a valuable account of its geology. He finally decided to make another trip into that country and invited Doctor Branner to accompany him. Doctor Branner had not yet completed his university course, but was much pleased at this opportunity to visit what was then a remote region, and he sailed with Doctor Hartt from New York for Rio de Janeiro in September, 1874. In later years, on his return to the United States, he received the degree of B. S. from Cornell University.

The expedition to Brazil was of much interest and importance, as the beginning of the first serious attempt to start systematic geologic work in that country, and it was greatly to the gratification of the two explorers that in the following year the Brazilian Government, under the Emperor Dom Pedro II, established a department to continue this work, under the name of Commissão Geologico do Imperio do Brazil. This was due largely to the efforts of Doctor Hartt and Doctor Branner, assisted by Brazilian scientists and others interested in this work. Doctor Hartt was appointed Director, with Doctor Branner as his assistant. Doctor Orville A. Derby, Richard Rathbun, and E. F. Pacheco Jordão were also on the same survey.

Doctor Branner's early exploration in Brazil was mostly in the coastal region of the State of Pernambuco and in the States of Sergipe and Alagôas, as well as on the Island of Fernando de Noronha, off the coast of Brazil. Large collections of geologic materials were rapidly assembled at the headquarters of the Commissão Geologico do Imperio do Brazil, in Rio de Janeiro, including many cretaceous fossils from Sergipe and Alagôas, and Doctor Branner did much to systematize and arrange them.

The work of the Commissão Geologico was carried on until 1877, when it was discontinued by the Brazilian Government. In later years other government organizations were instituted for geologic research, and Doctor Branner in some of his subsequent trips to Brazil worked in conjunction with them.

After the discontinuance of the first survey, Doctor Branner became associated with James E. Mills, a well-known American mining engineer engaged in operating gold mines in the State of Minas Geraes. In this work he rapidly became familiar with the older Paleozoic rocks of the region and the occurrence of gold and other ores in them; but,

though the scientific discoveries were of much interest, the financial results were not satisfactory, and in 1880 Doctor Branner returned to New York.

A few months later he again visited Brazil at the request of Thomas A. Edison, the inventor, to search for a vegetable fiber which would add strength to incandescent lights. He collected and tested many kinds of bamboo and other fibrous plants throughout Brazil and the neighboring countries, but only a few of them seemed to possess the desired qualities; and, though he traveled many thousands of miles in his search, he eventually concluded that the bamboos of Japan and China, already known to be suitable for the use in question, were cheaper and could be more readily obtained than those of South America. He returned to New York again in December, 1881.

In the following year he was commissioned by the United States Department of Agriculture to study the culture of cotton in Brazil, and especially the nature of the insects injurious to the cotton plant, with a view to securing information which might be useful in combating the same difficulties in the cotton regions of the United States. This work covered a large area of the country, and Doctor Branner and his assistant, Albert Koeble, found that the same insect which did the greatest damage to cotton in the United States existed to some extent in all cotton-growing regions of Brazil, but that it was particularly abundant in certain districts. In the spring of 1883 Doctor Branner returned to Washington and presented his results on this and other related subjects to the Department of Agriculture.

After this trip Doctor Branner temporarily ceased his frequent visits to Brazil and accepted an appointment on the Geological Survey of Pennsylvania to do topographic mapping in the Lackawanna Valley and neighboring country, one of the great anthracite and industrial regions of the United States. Prof. J. P. Lesley was director of the survey at that time, and his natural genius in topography was an inspiration to Doctor Branner in accomplishing similar work, not only in Pennsylvania, but subsequently in Arkansas and other regions. Doctor Branner also made important observation on the glacial geology of northeastern Pennsylvania, comprising the southerly extension of the great glacial region in these parts.

In the spring of 1885 Doctor Branner was elected Professor of Geology at Indiana University, Bloomington, Indiana, and in the same year received the degree of Ph. D. from that institution. The president at that time was Doctor David Starr Jordan, noted scientist and one of the foremost ichthyologists in the world. Through their combined efforts,

the university became a center for special instruction and research. Doctor Branner, with his wide professional experience, gave great effect to this movement, particularly in his work and instruction in geology, botany, and entomology, and he created a group of enthusiastic young students who later followed him to Arkansas and California.

In the spring of 1887 Doctor Branner was appointed State Geologist of Arkansas by Governor Hughes. One of the main reasons for the creation of the Geological Survey of Arkansas was the great excitement over the supposed existence of gold and silver in that State, especially in the Ouachita Mountains, which run westward from Hot Springs to what was then the border of Indian Territory, but now the border of Oklahoma.

Many companies had been formed to work these alleged mines. A thorough investigation was made by Doctor Branner and his assistants, and they were eventually forced to the conclusion that the mines then known were valueless and the few which contained a little gold and silver carried them in such small quantities as to be insignificant. This announcement of the first work of the Geological Survey caused great indignation among many of those financially interested in promoting the mines, the State Geologist was burned in effigy, and the Governor of the State was asked to remove him from office. Doctor Branner, however, stood firm, for he knew that he was correct in his conclusions, and he ignored the bitter efforts to destroy his professional reputation. Governor Hughes supported him, and the State legislature later endorsed his work and even increased the appropriation for continuing the survey. As time went on and the views of Doctor Branner were verified, the old antagonism changed to a feeling of remarkable confidence and respect.

Doctor Branner carried on his active survey in Arkansas for about five years, though he continued the work periodically for many years afterwards. It was doubtless the greatest accomplishment of his life, and, though accompanied with innumerable difficulties and most arduous work, the result was well worth his splendid efforts. Fourteen volumes were published and several were prepared but not published on account of lack of funds. They cover the paleontology, stratigraphy, petrology, economic geology, and other natural features of the State. The mineral resources were carefully investigated and discussed throughout the survey reports, but the purely theoretic geology was never forgotten as the economic possibilities were unfolded. The survey was thus of great importance from both purely scientific and economic standpoints, and when Doctor Branner finally left Arkansas to go to Stanford University his departure was regretted by the whole community.

Doctor Branner was assisted in his geologic work in Arkansas by geologists whom he had gathered about him from different parts of the country and by students who had followed him from Indiana University. A remarkable spirit of enthusiasm pervaded them all, and nothing manifested their loyalty to their chief more strikingly than when, in 1907, many years after the survey had closed, the surviving members presented to him a portrait of himself as "an expression of their high regard and of their appreciation of his example and inspiration as a geologist and as a man." In replying to this presentation Doctor Branner said: "To every member of that former organization I feel strongly attached. A more loyal and more faithful body of men can not be found anywhere. As long as the survey lasted, everyone exerted himself to the utmost to do honest scientific work and faithfully to serve the legitimate interest of the people of the State, and it is a great pleasure to know that our work in Arkansas is more highly thought of by the people of that State as time passes."

Doctor Branner was offered the Professorship of Geology at Stanford University in 1891, and resigned as State Geologist of Arkansas to accept it. The new institution had just been founded, and the president was Doctor David Starr Jordan, with whom Doctor Branner had formerly been associated at Indiana University. In California, just as in Indiana, these two men worked together and gathered about them a teaching staff of distinguished scholars from all parts of the United States. The result was that Stanford University rapidly became a recognized institution of advanced learning.

Doctor Branner entered upon his duties as professor at Stanford University in the winter of 1892, and for over a quarter of a century, during his official connection with it and after his retirement, he was active in its development, displaying the same energy and force that he had shown in previous work in other fields. His influence with his students was of an intellectual character which was truly astonishing and which impressed all who came in contact with him. In 1899 he was made vice-president and in 1913 was made president, though he still retained his position as head of the Department of Geology. Two years later he retired from the presidency, greatly to the regret of the university and the students, and was made president emeritus.

In addition to Doctor Branner's work at Stanford, he always maintained his active interest in Brazil, and in 1899 he went there again to study the great ocean reefs lying off the coast of Pernambuco, and to determine the geologic difference in their character. He had been familiar with this region ever since his early days in Brazil with Doctor Hartt,

but had not had an opportunity to study it in detail until this trip. The research covered some thirteen hundred miles of coastline, and a large amount of new geologic information was secured.

Doctor Branner was so deeply interested in exploration in Brazil that every time he visited it he found new districts which he desired to investigate on future trips. In 1907, therefore, he returned to study the black diamond districts of the State of Bahia and the geology of the States of Alagôas and Sergipe. He covered large areas of country and collected much important scientific information. The Brazilian Government had followed these explorations with much interest, and, realizing their important bearing on the industrial resources of the country, they employed Roderic Crandall, Doctor Branner's assistant, to continue the work after the latter had left Brazil.

Doctor Branner returned to Stanford after about six months' absence, but started again in 1911 with a new party for the purpose of making a study of the geology and biology of the Brazilian coast in the neighborhood of the mouth of the Amazon. Particular attention was given to the study of sea life on both sides of the vast volume of fresh water poured out by that river, and especially to its effect on the marine migration which moves along the coast from the shores of Pernambuco toward the mouth of the Amazon. The haunts and habits of the larger snakes in Brazil were also studied in detail and several specimens of boa were secured.

In consequence of the numerous trips of Doctor Branner to Brazil, the world today owes to his indefatigable efforts much of its geologic and other scientific knowledge, not only of the eastern part of the country, in the States of Pernambuco, Alagôas, Sergipe, Bahia, Minas Geraes, and Rio de Janeiro, where he did much of his work, but also of almost every other part. On some of his trips he worked in conjunction with Doctor Orville A. Derby, an American geologist who had been engaged in geologic work under the Brazilian Government and under the government of the State of São Paulo for many years. Doctor Branner was assisted on some of his trips by H. E. Williams, who had been with him on the Geological Survey of Arkansas, and by Roderic Crandall, who had gone to Brazil with him and who in later years continued work which he had begun. Others of his own countrymen were also associated with him.

Doctor Branner was on most cordial terms with the Brazilian geologists, many of whom had done excellent scientific work, and some of his own exploration was done jointly with them. The noted Brazilian geologist, Doctor Miguel Arrojado R. Lisboa, was among his particular

friends. He was also on terms of intimate good fellowship with the officials of the old Empire of Brazil and of the United States of Brazil, which followed it, and nothing illustrates this better than at the time of his death the Chamber of Deputies of the Brazilian Government passed resolutions of condolence.

Doctor Branner, throughout his whole career, took a great interest in the subject of seismology, but this interest was much stimulated after the earthquake in California in April, 1906. Soon after that calamity he was appointed a member of the State Earthquake Investigation Commission of California by Governor Pardee. In addition to this commission, one of the direct results of the calamity of 1906 was the formation of the Seismological Society of America, of which Doctor Branner was a charter member. He was president of the society from 1910 to 1914 and was chairman of the Publication Committee from 1911 to 1921. In 1915, when widely divergent opinions were being expressed regarding the questions of earthquakes and landslides as affecting the Panama Canal, Doctor Branner was appointed a member of a committee of ten which was commissioned by the United States Government to visit the Canal Zone and investigate these matters.

Most of his seismological work, however, was done in California, where he accomplished important results in collecting data which could be practically applied in the limitation, and in some cases the avoidance, of the destruction caused by earthquakes and by the disastrous fires which often follow them. Prof. Sidney D. Townley, of Stanford University, who is himself a leader in seismological research, in writing of Doctor Branner's connection with the Seismological Society, says in its Bulletin of March, 1922, that "in the death of Doctor Branner the Seismological Society has lost one of its staunchest supporters. He gave liberally of his time, energy, and funds in support of seismological projects; he was the founder of the Society's Bulletin, and it was he who provided the ideas and ideals, the manuscript, and the funds for the successful continuance of this publication through a difficult period of ten years; it was he who obtained a gift of $5,000 for the society, and he who by never-tiring efforts trebled its membership; it was he who revived a nearly defunct society in 1910, and through ten years of constant effort built up an organization of merit, worth, and usefulness."

After Doctor Branner had retired from the presidency of Stanford University he retained his home there and devoted much of his time to work on many scientific problems which his busy life had previously prevented him from finishing. During this period he completed a geological map of Brazil, which was published under the auspices of the

Geological Society of America, and with the map he wrote explanatory texts in both English and Portuguese. The great amount of geologic detail displayed over vast areas of country in this map is a mute but eloquent testimony to the research, the learning, and the untiring efforts of its author.

Doctor Branner was primarily a geologist and his work covered a wide field in various branches of the earth sciences, including paleontology, stratigraphy, mineralogy, seismology, and economics; but he also accomplished important work in botany, entomology, and other branches of biology. He was one of the last of the old-time scientists who were learned in many branches of natural history, before the extreme specialization of modern times had compelled research workers to confine themselves to narrow lines of scientific investigation.

In addition to his accomplishments as a scientist, he was a linguist of unusual ability, a remarkable educator, and a strong leader of men. He was learned in both ancient and modern languages; Latin and Greek were thoroughly familiar to him; and in modern languages he was preeminently a scholar in Portuguese, in which he wrote a grammar for English-speaking people, a textbook of geology for the Brazilians, and an explanation of his geologic map of Brazil, as well as numerous geologic reports relating to that country. In his later years he translated from the Portuguese the History of the Origin and Establishment of the Inquisition in Portugal, by Alexandro Herculano. Other modern languages also came easily to him and assisted him greatly in his various travels.

As an educator, he achieved remarkable success with his students. His sympathy and his interest in their work did much to inspire that feeling of regard and loyalty preeminently observable in them. His forceful, fearless, and intellectual personality, his wide experience in scientific research in many regions, his broad vision, not only in his work, but in his knowledge of men, gathered around him, at Indiana University, on the Geological Survey of Arkansas, at Stanford University, and on numerous trips to Brazil, a group of followers remarkable both in their numbers and in their professional success in later life. His students have spread over almost every part of the world and an unusually large percentage of them have done honor to their instructor and chief. As he himself said in later years in referring to certain honorary recognitions which he had received in his profession, the greatest honor of all is that which comes to one from having men "who have been his students doing good and honest work in every quarter of the globe."

Doctor Branner married, in 1883, Miss Susan D. Kennedy, of Oneida,

New York, a graduate of Vassar College. They had three children—a daughter, now married, and two sons. They all graduated from Stanford University, and his two sons and his son-in-law enlisted as volunteers in the American Army during the recent war with Germany. In a letter to the writer shortly afterwards, Doctor Branner related how he also had tried to enlist, but was not accepted on account of age. That never-failing spirit to face boldly and fearlessly whatever difficulties fell to his lot was with him to the last. He died on March 1, 1922, in his seventy-second year.

Doctor Branner was a member of numerous scientific societies and had in many cases received distinguished honors from them. He was a member of the National Academy of Sciences, the American Philosophical Society, the Geological Society of America (President, 1904), the Society of Economic Geologists, a Fellow of the American Association for the Advancement of Science (Secretary, Section E, 1888-1889; Vice-President, 1890; President, Pacific Division, 1916); Chairman Cordilleran Section, 1913; Seismological Society (President, 1910-1914); Mining Engineers, Washington Academy, London Geological Society, Société Géologique de France, Société Belge de Géologie, Instituto Historico de São Paulo, Brazil Academy, Instituto Historico Geographico do Brazil, and many other scientific organizations. He was also an associate editor of the Journal of Geology.

Among the many scholastic and honorary degrees received by Doctor Branner during his career may be mentioned: B. S., Cornell, 1882; Ph. D., Indiana, 1885; LL. D., Arkansas, 1897; Maryville, 1909; California, 1915; Sc. D., Chicago, 1916. In 1911 the Hayden Medal Award was conferred upon him by the Academy of Natural Sciences of Philadelphia in recognition of his personal contributions to the science of geology.

The remarkably wide sphere of subjects studied by Doctor Branner and on which he wrote to a greater or less extent is shown by the following bibliography, comprising almost four hundred titles:

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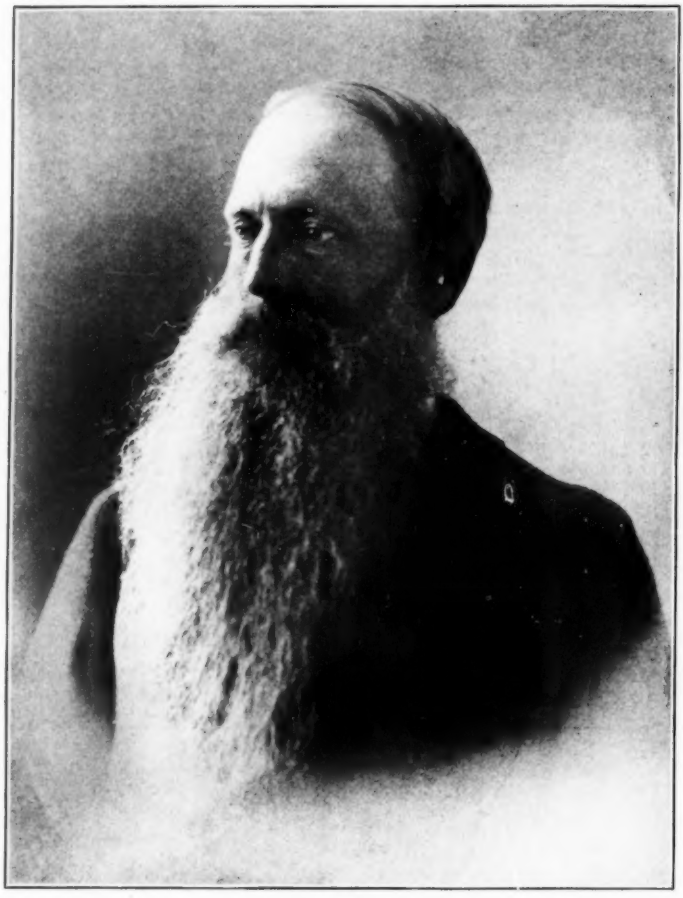

Raphael Pumpelly

MEMORIAL OF RAPHAEL PUMPELLY[1]

BY BAILEY WILLIS

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FOREWORD

Pumpelly's place is among the great explorers. He inherited the spirit; his environment gave the motive; he achieved the career by virtue of his physical endowment, his high courage, and his mental and moral fitness.

His interest in geology was first aroused by his mother, an unusually gifted woman, and was fixed by early incidental opportunities for observations in Germany and Corsica, followed by a chance meeting with the German geologist, Noeggerath, which led to his going to the mining school at Freiberg. He used his profession of mining engineer, but never devoted himself to it. He served his adopted science, geology, but not exclusively; yet his contributions to its principles and knowledge remain unchallenged after thirty to fifty years of later intensive research along the same lines. He cherished for forty years a dream of carrying out investigations in the archeology and ethnology of the Asiatic and European races and at the age of three score and ten realized it with that same thoroughness and devotion to truth which characterized all of his scientific studies.

BOYHOOD

Pumpelly's paternal grandfather fought through the French and Indian wars and the Revolution. At the close of the latter he moved

[1] Manuscript received by the Secretary of the Society, January 26, 1925.

out onto the then frontier of New York, near Ithaca, with his four sons, of whom John, the oldest, had spied out the land and William, a blond, six feet two in height, became Raphael's father. William is described by his son as a man of noble features and fine presence, of equable and kindly temperament, and with broad sympathies. He transmitted his nobility of spirit, his optimism, and his kindly sympathetic nature to his son.

Raphael's mother came of families that had ruled colonial Connecticut. He says of her: She was of medium stature, erect and energetic, affectionate, and artistic in temperament. He was not trained, as she was, to be an artist, but he inherited from her an appreciation of the beautiful, which she cultivated, and it is evident from his reminiscences that she exercised a dominant influence upon his intellectual and moral development from boyhood on.

Raphael Pumpelly was thus born of English colonial stock, pioneering on the forested frontier, engaged in surveying the boundaries of new states and land grants, clearing the timberlands, exploiting the wealth of the wilderness, and building up the young Commonwealth of New York. Owego, his birthplace, was but forty-five years old when he was born; yet such had been the energy of the settlers that the forest felling, the rafting of lumber down the Susquehanna, the building of roads, and other truly pioneer activities had begun to give place to the established life of an American country town, with good schools and schoolmasters whose wholesome, though stinging, discipline Raphael remembered after threescore years and ten.

N. P. Willis, writing when Raphael was ten or twelve years old, thus described the scenes among which the boy grew up:[2]

"At Owego there is a remarkable combination of bold scenery and habitable plain. A small, bright river comes in with its valley at right angles to the vale and stream of the Susquehanna, forming a star with three rays or a plain with three radiating valleys, or a city (in the future, perhaps) with three magnificent exits and entrances. The angle is a round mountain, some four or five hundred feet in height, which kneels fairly down at the meeting of the two streams, while another mountain of an easy acclivity lifts gracefully from the opposite bank, as if rising from the same act of homage to Nature. Below the town and above it the mountains for the first time give in to the exact shape of the river's short and capricious course; and the plain on which the town stands is enclosed between two amphitheaters of lofty hills, shaped with the regularity and even edge of a coliseum and resembling the two halves of a leaf-lined vase, struck apart by a twisted wand of silver."

[2] N. P. Willis: Rural letters, letters from under a bridge, 1849.

Of the Susquehanna Willis wrote:

"This delicious word, in the Indian tongue, describes its peculiar and constant windings; and I venture to say that on no river in the world are the grand and the beautiful in scenery so gloriously mingled. The road to Owego follows the course of the valley rather than of the river, but the silver curves are constantly in view; and from every slight elevation the majestic windings are seen, like the wanderings of a vein, gleaming through green fringes of trees and circling the bright islands which occasionally divide the waters. It is a swift river and singularly living and joyous in its expression."

We may not assume that the scenery impressed the boy as it did the poet, but the river played an important part among the youngster's early stimuli. Twice nearly drowned, he feared to swim beyond his depth; yet, fearing ridicule even more, he dared the boys to follow him on thin ice, or to shoot a dam on a plank, or (most daring of all) to navigate the river in flood on a cake of ice. This last, he records, found no takers and twice nearly finished him. He afterwards looked back on this "bravado" as a most valuable part of his training, for "it taught quickness of perception, the instant cooperation in emergencies of brain, hands, and feet, and that balance between caution and action that forms a basis of judgment."

But it was not alone as a dangerous playfellow that the river entered into the boy's life. Its swift current, coming from who knows where and flowing on into the unknown, became to his adventurous spirit a symbol of life, leading him on, unconscious of its influence, to that career of exploration for which he was so eminently fitted. He knew nothing of the lands he was to visit—Corsica, Arizona, Japan, China, or Siberia. He had no idea of the geological and ethnical problems in which he later interested himself. All that was around the bend. But the shining river, flowing swiftly westward in gleaming curves, can not but have led his fancy on, as he watched the great timber rafts float out of sight, or listened to stories of voyages beyond his ken.

He studied at the Owego Academy, perfunctorily apparently; his real school was out of doors. There he trained his faculties, very much as young Indians had done in the same environment but a few decades before him. His self-respect had not developed beyond the childish principle that one should not be found out. But a piratical downward course on which he and his youthful followers had entered was brought to a sudden close by a serious offense, and he was led to a sense of responsibility for his acts through the searching, though loving, reasoning of his mother and the sound chastisement she gave him in due sequence. Following this, when eleven years old, he was sent away to school to General

Russell's at New Haven, where he spent the next six years, developing by his own account into a manly and honorable, but daring and irresponsible, youth.

In the natural course of events Raphael would have followed the lead of a majority of the scholars of General Russell's Academy and have entered Yale; it was therefore in keeping with the scheme of his life that he went to Europe instead. The thought of so doing was first suggested by his chum, who in the end did not go, but it was the cordial interest taken by his mother in a European journey which made possible the realization of the boy's unusual proposal. It is evident that he and she were comrades in initiative, congenial in spirit and in tastes, and that she, no less than he, looked forward eagerly to the pleasures of a tour abroad. In 1854 the parting on such a journey was a very different thing from what it is today, but her eager, artistic spirit rose to the opportunity without thought of consequences, as was ever his instant impulse.

The experiences of an American boy of seventeen or eighteen as a free lance in Germany or France are the reactions of his character with his environment, as definitely fixed as are chemical combinations. Pumpelly's were no exception. Frankly interested in everything about him—languages, social ways, or scenery—he met every new impression eagerly, instinctively gathered the good from it and passed on in search of further novelty. He acquired French, German, and Italian by listening and talking rather than by study. He readily adopted the ways of congenial companions and made friends among young and old; but one experience of students' carousing disgusted him. He turned rather to his independent life, attending lectures on all kinds of subjects for what he could learn of the language and wandering far afield among the picturesque and romantic scenes of central Germany. Long afterwards he remembered that.

"During the month of May (1855), wonderfully beautiful that year, I tramped up and down the valley of the Rhine and into the interior on each side. To my young imagination that month was a delight. The valley was as yet untouched by the wand of modern industrial desecration, the air was still pure, the sky serene, and the castles crowning the hills were still real moss- and plant-clothed ruins.

"Who can describe the effect of it all on the impressionable imagination of a boy fresh from the land of modernity; the charm of the ever-varying scenery, the vineclad slopes, the echoing cliffs of the Siebengebirge, the castles, the Lorelei-haunted Drachenfels, and the romance and legends of the past?

"Then to me there was another interest which seemed to intertwine itself with the romance and poetry of the region. Here for the first time I came in contact with eruptive rocks, the striking sanadine trachyte cliffs of the

Drachenfels and the porous sapphirine-bearing lavas of the Laacher See. Truly I was entering, though gropingly, into geology through the gate of romance."

Thus Pumpelly gives us the clue to his interest in geology; but the picture of himself is not complete without the added touch of interest in his fellow-men, which was always the dominant one of the two. He continues:

"Bon Cœur (a Newfoundland dog) was always with me, sleeping on or near my bed at night and tramping alongside by day. Admired by all, he introduced his master to many; so that I never lacked chances to talk with men and women of every class, whether residents or travelers."

His attention had been attracted, when he was still a mere boy, to the fossils which are abundant in the strata of the gorges about Owego, and a teacher with whom he had wandered along the Bronx near New York had stimulated his interest in the minerals and metamorphic rocks of that region. While at Hanover he collected ammonites, crinoids, etcetera, from the Deister Mountains, and, hearing that there was a geologist in the neighboring town of Hildesheim, he made an unsolicited visit on the well-known paleontologist Von Roemer in order to see his collection. He was kindly received, and the scientist then and afterwards gave him further insight into the realm of geology and the line of relationships which link extinct forms with the living. Darwin had not then "hurled the bomb of evolution," but the seeds of that understanding were planted in Pumpelly's mind by von Roemer.

More than a year was to pass, however, before his growing interest in geology was to give a definite purpose to his education. In the meantime he continued to develop the habit of observation, with special reference to geologic phenomena and human nature. He made a summer excursion in Switzerland, where the grandeur of the mountains did not fail to make an imperishable impression on his memory. He spent part of a winter in Paris, and left there for Naples to recover from a cold which attacked his lungs. At Naples he resumed his roaming about the country to satisfy his curiosity—we had better call it, rather than interest—in the volcanic phenomena and in the romantic background of Nature and people. He wrote:

"I haunted Vesuvius. I liked to trace the destroying streams of lava that during centuries had coursed down the slopes to the sea, and I noticed as well as I could their difference in structure. Then there was the pleasure in searching for the fragments of limestone hurled out from great depths. They had been changed in the subterranean laboratory to marble, and often contained a variety of beautifully crystallized minerals peculiar to Vesuvius.

Of course, I did not know anything about these minerals, except that they were beautiful in my eyes."

He visited Solfatara, where in the extinct crater he saw the rocks undergoing decomposition by gases with the formation of new minerals. He realized that rocks and minerals are not dead.

"Their stories were in process of forming before my eyes, though to me still unreadable. Having as yet no knowledge of this alphabet, chemistry, I began to draw more remote inferences from grouped observations, and to generalize. Here were two neighboring volcanoes, each showing a different kind of activity; in one the activity was constructive, in the other it was destructive."

Pumpelly thus was led by his own observations to the inference that "heat and gas and water were active agents in building up one volcano and destroying another," but that there was some other factor beyond his reasoning. He traversed the volcanic formations around the bay of Naples until he could have made a geologic map of them, had he known how, and the field of volcanism, with all its diverse phenomena, became correlated in his mind as a whole.

The invaluable character of this effort to unravel a skein of intricate geologic relations, even though with one-eyed understanding, was later fully realized by Pumpelly. It may have been with the kindest purpose that in 1879 he sent a very young and wholly inexperienced geologist, without assistance, to investigate the geology of the iron ores of the eastern United States. It is certainly a testimony to his kindliness toward young men that he never uttered a word of criticism of the results.

But Pumpelly's interests were never single. Referring to his roamings around the historic bay, he says:

"The stately lines of Virgil haunted me and, lying on the citadel mound of old Cumæ and on the heights of Baiæ, I reveled in daydreams—the Trojan wanderers and the Sibyl, the Phlegraem fields and Avernus, and the brilliant life of Baiæ all became real. Those weeks are in my memory one continuous happy dream."

There followed a summer in Corsica, of which more anon, and the autumn of 1856 led the wandering youth and his mother, who had been his constant companion wherever it had been practicable, to Vienna, where he by chance strolled into a meeting of the Deutscher Naturforscher Verein. It was a turning point in his life.

Noeggerath was then a great name among German geologists and it belonged to a kindly old man whom Pumpelly happened to address on entering the meeting. Their conversation resulted in an acquaintance and excursion together and Noeggerath, recognizing the boy's qualities

and enthusiasm, advised him to go to the Royal Mining Academy in Freiberg, Saxony. His advice was accepted and thus the decision was made between the interest in geology and the attraction toward a wider, general education, which might have led to concentration on history and ancient literature. Even so, Pumpelly's inclination toward studies in those branches of science which deal more directly with men, such as ethnology and the evolution of civilization, was never lost to him. It led him during his first journey across Asia to grasp the problem of the ancient migration of the Aryan race, and later, in his seventieth year, to return to those deserts to search for buried cities in the kurgans of Turkestan.

Freiberg, 1856 to 1860

Freiberg in the middle of the nineteenth century was approaching its centennial (it was founded in 1765) and had great reputation, as well as established traditions of training, for the profession of mining. It was the foremost school of practical mining in existence. It drew students from all countries. To be a Freiberg graduate was to hold a diploma of the highest grade in the profession. Having been established at Freiberg because of the ancient mines still being worked there, it was an outgrowth of practical experience, and practice dominated the then relatively simple theories of mining and metallurgy in the curriculum of the school. Today the requirement of scientific knowledge of geology, chemistry, and physics, in their vastly more complex applications to the arts, has wrought a change in the training of the mining engineer and metallurgist. Although some great schools still use working models of machinery and other equipment for demonstration, even these tools have been subordinated or abandoned in the more advanced curricula, and training in practice has given place to founding in principles. Things have changed at Freiberg also. The mines, after having been worked for some years in order to maintain the school, which sprang from them, have been shut down, and with the growth of mining schools in other lands, especially in America, the former center of the art has lost its preeminent position. In Pumpelly's student days it had, however, no equal.

The old Freiberg held another tradition worthy of imitation and which Pumpelly greatly appreciated. It was *Gemuetlichkeit*. Militarism had not yet chilled the genial German spirit. Authority and learning, instead of presenting a barrier to youthful aspirations, opened the doors and pointed the way blazed by experience. Cotta, Weisbach, and Breithaupt met their students in the true fellowship of knowledge and became

in a sense their comrades while retaining their respect. Pumpelly entered readily into this comradeship. Referring to the frequent excursions taken with Cotta, he says:

"During the years I was in Freiberg these trips covered not only the neighboring region, but extended to Bohemia and Thuringia, sometimes lasting a week or even longer. In some of these, in the holidays, several of the other professors joined and the whole became a jovial picnic. These men, old and middle-aged, were quite as good comrades as any of us. Outside of the lecture room they were young as we were; we liked to mingle with them at the restaurant tables, drinking beer, smoking, or telling stories, or in serious talk; and they joined us in the same spirit. I hold this to have been an important element in education. It is a phase that seems to be lacking in our universities and is only partially represented in our conferences on special subjects. Professor Shaler, of Harvard, was the only American instructor I can recall who was a representative of the type of these men in that respect. Bless them and him, for they are remembered with affection and gratitude."

It may not have been difficult for Pumpelly's generous spirit to learn this lesson of encouragement for the young. That he did learn it and practiced it in all his relations with associates of every degree, none who has come into contact with him would fail to testify. It was his influence, joined to that of Chamberlin, Gilbert, and Powell, which introduced into American geology the habit of give and take in research. It has become so general that he who does not exchange ideas with his fellow or fails to give credit where credit is due achieves something of the unenviable reputation of a miser, as one who is to be condemned for his avariciousness of thought and to be pitied for what he loses.

It was typical of Pumpelly's impatience of close thinking that he never acquired a thorough knowledge of mathematics. This was a great drawback to him, on entering Freiberg as well as later, but as a student he took heroic measures to overcome his deficiency. Finding himself obliged to take private lessons and having no time during the usual waking hours, he hired a student to bring him a tub of cold water at half past three in the morning, pull the bedclothes off him, and start the fire in the big porcelain stove—all under pain of quick dismissal if he failed. This discipline was kept up during three years and was followed each morning by a lesson in mathematics over the coffee cups. The procedure was, however, only partially successful. Pumpelly never developed a memory for detailed minutia, such as the mathematician must possess. He saw the world as the condor sees it, yet could focus his vision intently for the moment.

Cotta seems to have been the chief influence in his studies at Freiberg, but Breithaupt interested him in crystals and in their systematic rela-

tions. Teaching crystallography without mathematics and by the use of models, he pointed out the relationships, an understanding of which transforms the barren description of figures into a fertile field of thought. The study of paragenesis and pseudomorphs, pursued under that able teacher, was developed later in Pumpelly's contributions to metasomatism, especially of the Lake Superior copper ores.

It is difficult after three-quarters of a century to translate our thought to the stage of development of the sciences in that day. We no longer refer to the writings of the men who were then the ultimate authorities: Humboldt, von Buch, Cotta, Lyell, Murchison, Elie de Beaumont, d'Orbigny. Science was then exceedingly simple, but it opened a vast prospect, a fascinating opportunity to a young man with a genius for exploration.

Pumpelly remained at Freiberg until 1860, when, having completed his courses of study, he returned via Paris to America. He had left home as a boy of seventeen; he came back not only grown to manhood, but with a knowledge of the great world, unspoiled yet experienced. Among his companions at Freiberg had been James D. Hague and the brothers Henry and Louis Janin, all three of whom achieved enviable reputations in their profession. They, however, pursued its more technical opportunities, while Pumpelly, after a first essay at mining, struck out into the broader fields of geological exploration.

Corsica, 1856 to 1857

It was foretold of Pumpelly, when he was but seventeen, that he would make long journeys by sea and through dangerous lands, but that he would escape, unless taken unawares from behind by some one of his companions. He tells us that the saying made him cautious as to conditions in his rear and elsewhere—that is, it put him on the alert and enabled him to pass safely through various dangers. Whatever the effect of the prophecy upon his imagination, he undoubtedly owed much to his keen, highly developed habit of observation. Again and again in the story of his life it happens that an incident, too slight to be commonly noticed, gave him warning and enabled him to act effectively, in time.

Two summers spent in Corsica, one as a rambler on the lookout for bandits, the other as a companion of the bandits on the lookout for gendarmes, introduced him, while still a youth, to the thrilling delights of a life of romantic risks.

He first saw Corsica while en route from Marseille to Naples, and as his steamer slowly passed the peaks, which rise to nearly ten thousand

feet above the Mediterranean, he longed to roam among them. The realization of his desire came about in a manner so characteristic of himself that it can not be omitted.

One beautiful day in May, 1856, Pumpelly, having grown weary of Florence, where he was with his mother, left her for a day or two at most, not knowing whither fancy might lead him. His impulse took him by train to Leghorn; then by a chance steamer to Bastia, in Corsica, and on to an idyliic visit with a forester and his charming Parisian wife; thence he climbed among the mountains, wandered carefree with the Corsican shepherds, shared their primitive life, and steeped himself in the wild beauty of the heights and in freedom. In September he returned to his mother, to find that his occasional notes, sent back through shepherds, had never reached her, and he was mourned as dead.

There are no more fascinating chapters in Pumpelly's reminiscences than those which describe his two summers among the Corsican shepherds, in whom he found the stern character and virility of ancient Rome, the piety of the early Christians, and the fierce spirit of the Italian vendetta. But only the geologic observations which he made incidentally are appropriate here.

During his early excursions he penetrated to the heart of the island and saw for the first time the core of a granitic massif laid bare by the profound gorges. Later he reached the porphyries of Monte Baglia Orba and observed the variations of color and texture which distinguished the, to him, still unknown rocks. He recognized them, however, as the same that he had seen in the ruins of the palace of the Cæsars in Rome. Noting that one dike would cut through another led him to infer differences of age between the two, and he became interested in tracing out these relationships. The sketches he then made in his notebook (he was but nineteen) afterwards helped to introduce him to Noeggerath, and thus to open the way to Freiberg. During his second visit to the islands he made a systematic study of the porphyries and correlated the dikes according to their differences in age and the rocks they traversed.

Pumpelly also recognized evidences of glaciation in the mountains of Corsica, and thus established the fact that the Glacial Period had left its traces there. His account, published in the Neues Jahrbuch für Mineralogie, describes the polished and striated surfaces of the hard porphyries, the transported blocks of rocks not found in place on the slopes where the erratics lie, and a terminal moraine. Referring to three great fragments, 30 to 40 feet through, which were so piled on each other as to form a cave in which he camped with shepherds, he argues:

"Now that one no longer believes in floods of boulders, what transporting agent other than glaciers can have operated here to carry these great rocks down a valley where the average slope is not far from 8 degrees, and to have left them in their present positions without having rounded them off in the least."

We must remember that Agassiz's hypothesis of glaciation was then in its infancy, and what is today a commonplace of elementary science was an unfamiliar, somewhat daring inference; but, accepting the facts he observed, Pumpelly ranged on into the realm of hypothesis, as was ever the habit of his far-reaching imagination. He reasoned that glaciation should depend on heavy precipitation, as it does, and he sought for geographic conditions to which a greater precipitation in Corsica at an earlier epoch might be ascribed. It was generally believed that the Sahara Desert had formerly been covered by a sea, and he found in that hypothetical water body a source of moisture which the southerly winds should have carried to the Pyrenees, the Alps, and Corsica. He sought confirmatory evidence, not without success, and he was encouraged by Cotta and Reich, his instructors, to write out his hypothesis. They even suggested that it was worthy of the degree of Ph. D. from Heidelberg. Nevertheless, when he came to write down his observations he excluded the theory, because he had no definite evidence that there ever had been an inland sea covering the Sahara. Thus an instinctive caution characteristic of the true scientist withheld the young investigator in his first original essay from falling into error.

In these his earliest steps in geology Pumpelly employed two methods which afterwards characterized his geologic studies and which he has passed on. He grasped the salient facts in bird's-eye view, and from them framed an explanation, an hypothesis. This he tested, modified, proved, or discarded, as additional facts appeared, going on, *pari passu,* to another hypothesis if the first was proved wrong. It is the method of *Sequential hypotheses* in contradistinction to that of *Multiple hypotheses.* The former is as essential and as appropriate to reconnaissance work as the latter is to exhaustive research. The capacity to seize essential facts and to detect their correct relations at a glance is vital to success in exploration and is an attribute of the great explorers. But it requires to be held in check by detailed studies of key phenomena, of those details in which the true relations are demonstrable on a small scale, perhaps, or for a single locality. Only thus can the observer avoid superficial and probably erroneous conclusions. The power thus to guard against false inferences by painstaking investigation of details of key facts is too often lacking in men of the eagle eye, but Pumpelly had it. It was demon-

strated even in his earliest work by the care with which he sketched the relations of the porphyry dikes of Corsica.

Arizona, 1860 to 1861

Arizona in 1860-1861 was a land of hell and sudden death. A majority of its white inhabitants cared little what came after. They knew no law save their own caprice; were exiles from that portion of the frontier where laws could be enforced. Mexican peons constituted another part of the population, indispensable laborers, dangerous cutthroats. The small body of United States soldiers, who had kept a semblance of order, were withdrawn in the spring of 1861, leaving the ranchers and miners to that extermination which had been sworn by the Apaches, whom outrages of every sort had driven to desperation.

Into this lawless land came Pumpelly as mining engineer in charge of the Santa Rita Mine. He was twenty-four. Behind him were Freiberg, Vienna, Rome, and Paris; Corsica also; and if in that far island he had lived among outlaws, they were so only in opposition to the established order. Their own code they obeyed implicitly. Here was a land without law, where a man's only safeguards were physical strength, cool courage, and alertness. Pumpelly possessed these qualifications in high degree. He could ride and shoot, but, most important, he let nothing escape his observation. His cat, sniffing the breeze, warned him of Indians who had just killed his associate, Grosvenor. He himself was one of the very few mining engineers who escaped massacre.

The problems presented by the geologic structure of the mine and the smelting of the ores fully occupied the young engineer during his first few months at the mine. The Santa Rita was reputed to have yielded fabulous wealth to the Spaniards. It was expected to yield accordingly to the new American company, which, like many another, thought to acquire riches for nothing. The working capital was very limited, equipment there was none beyond what the natural resources of the region afforded. The richness of the ores had been exaggerated or the richer ores had been exhausted. The general facts of the geology, the existence of two distinct groups of mineral deposits of which the older was the more valuable, the general character of the ores and their proper metallurgical treatment, none of these now well-known things had been worked out. Pumpelly faced an intricate complexity of problems, which he must solve unaided and without essential materials. He has put the situation into a paragraph:

"We needed fuel, fireproof furnace materials, machinery and power, and the supply of these furnished by Nature in Arizona was of a kind to necessitate

a great deal of trouble and experimenting when taken in connection with the peculiar character of our ore. The season was promising to pass without our hacienda being troubled by Indians, when one morning our whole herd of forty or fifty fine horses and mules was missing. Several times during the remainder of the winter and spring we were attacked by Apaches and our mines were the scene of more fighting than any other part of the Territory."

When the Territory was abandoned to the Indians by the withdrawal of the soldiers, those in charge of the few isolated mines which had been opened could only take such measures as might most speedily and safely enable them to save the movable property and escape. Money was needed and could be had only from the ores. The Santa Rita had no sufficient supply, since the Indians had for some time made it impossible to work the mine, but payment of a debt due from the Heintselman Mine was accepted in ore worth $2,000 a ton. It cost the lives of two Mexicans and of Grosvenor to get the ore to the Santa Rita, where Pumpelly and Robinson, the bookkeeper, were thus left to carry on with the aid of a chance American and their unpaid Mexican peons. The Mexicans, armed with rifles to withstand the Indians, were scarcely less dangerous and were not allowed to cross a dead line. Wood had to be cut, hauled in, and burned to charcoal. The furnaces, standing on a point between two ravines, lighted up every object near them and exposed the workers constantly to the fire of the Apaches. Pumpelly's chief smelter was shot and he was obliged to finish the separation of the silver and lead almost without sleep for fifty hours or more.

"The two other Americans, revolver in hand, kept an unceasing guard over the Mexicans, whose manner showed plainly their thoughts. Before the silver was cool we loaded it. We had the remaining property of the company, even to the wooden machine for working the blast, in the wagons and were on the way to Tubac, which we reached the same day. Here, while the last wagon was being unloaded, a rifle was accidentally discharged and the ball, passing through my hair above the ear, deafened me for the whole afternoon. Thus ended my experience of eight months mining in an Apache stronghold."

Truly he may be said to have borne a charmed life.

Geologic studies could not well be carried on satisfactorily under the conditions which governed Pumpelly's movements during that adventurous eight months. Yet he assembled observations bearing on the rocks with which the ores are associated, as well as on the mineralogical nature of the ores themselves and on the sequence of the minerals. These he laid before the California Academy of Sciences in August, 1861. In view of the great advances which have since been made in all branches of mining geology and of the development of the mining districts of

Arizona, his essay is chiefly of historical interest, a milestone from which to measure how far we have come and what a fruitful epoch in science his long life covered.

Japan and China, 1861 to 1864

At the age of twenty-four Pumpelly was a man of fine physique, combined with a frank, easy manner and a record of achievement. He had been a leader among the students at Freiberg, not because he sought leadership, but through his native qualities—initiative, courage, ability, and good fellowship. His wide and varied associations with all classes of society had given him the bearing of a gentleman of the world, a gentleman without blemish. His unique experiences in Corsica, described with the gift of a born raconteur, had early given him a reputation for daring and geologic understanding, and his success in salvaging the property of the Santa Rita Company under desperate circumstances had confirmed that reputation in America. He was already a prominent figure in his profession.

Thus it happened that he was one of two experts appointed by our Government in response to a request from that of Japan for a geologist and a mining engineer to explore certain lands in southern Yesso and, possibly, to introduce foreign methods of mining and smelting.

Feudal Japan pondered long and gravely the vital question of rank before receiving the experts, Pumpelly and W. P. Blake, but upon assurances from our Minister finally accorded them distinguished standing, such that they were called upon first by the Governor of Yesso. It would have been practically impossible for them to have executed their commission otherwise, since they could hardly have escaped insuperable opposition, if not death, from the natives, had they not been guarded accordingly. There was with very good reason a strong anti-foreign party in Japan, which opposed every move of the weak central government toward opening the empire to the outside world, and the incident of the engagement of the two experts was used as a ground of attack by the great nobles. They accused the Taikoon of throwing the resources of the country open to foreigners, and after a year forced the government to bring the engagement to an end.

Pumpelly has left the record of his observations in Japan in his book of travel, "Across America and Asia," and in the work "Geological Researches in China, Mongolia, and Japan." The former is a graphic description of the strange peoples, their lands, their cities, customs, and politics, sympathetic in feeling and liberal in attitude. The latter consists, so far as Japan is concerned, of geologic itineraries in the island

of Yesso. The author describes them as hasty jottings, made during reconnaissance journeys, at a time when he expected to make a much more thorough study of the geology of Japan. They served, nevertheless, to enable him to distinguish the foundation rocks of the island, a sequence of metamorphosed sediments penetrated by granitic and basic eruptives, and the superjacent volcanic deposits of various kinds. His studies in Corsica and of Vesuvius thus came to his aid on the other side of the globe. He also noted the coastal terraces and identified them as recently elevated, finding marine shells in which the organic matter was not entirely decomposed. The distribution of the various rocks, so far as he was able to observe them, is shown in a sketch map, one of the earliest geological maps of Japan.

Driven out of Japan by the daimios, whose opposition to the more liberal policy of the Tycoon led practically to a state of civil war, Pumpelly proceeded on his own resources to China, to gratify his taste for exploration in that unknown land, so recently opened to modern travelers.

In speaking of the reopening of China, we are apt to forget that between 1541 and 1720 Jesuit missionaries penetrated to every part of the Empire, that they exercised an important influence at the court, and almost succeeded in converting the Emperor himself to Christianity. China was then open to Europeans, but was closed by the anti-Christian agitation about 1720 and remained so for more than a century. During that time China stood still, while Europe advanced by leaps and bounds. America stood in the vanguard of that advance, and Pumpelly, coming from the frontiers of America, yet equipped with the science of modern Europe, looked upon the ancient people through youthful eyes, the eyes of hope and fair play. "Across America and Asia" contains a chapter on the Chinese as emigrants and colonizers, in which the author analyzes the relations of the Chinese and Caucasian races with an intimate understanding of the social and economic problems, and the dedication of that work, written in 1870, expresses the optimism with which he characteristically regarded the long future:

> **"As so many of the following pages relate to experiences illustrating the wisdom of that diplomatic policy which, in bringing China into the circle of interdependent nations, promises good to the whole world, I dedicate them to the chief author of that policy—to Anson Burlingame."**

Fifty years have passed since that was written, and the impartial observer must admit that much evil has developed from the meeting of the races, as well as good. Nevertheless, one who has trodden in Pumpelly's footsteps, who knows how often the patient, long-suffering Chinese have

risen Phœnix-like from chaos, and who believes in the inevitable supremacy of justice and fair play among Americans, must agree with Pumpelly in his faith in the ultimate preponderance of good to flow from the establishment of mutual relations among the races of men.

Pumpelly was the pioneer geologist of China. The scientific labors of the Jesuits were purely geographical and could not, in view of the lack of geological knowledge at that time, have yielded any understanding of the rocky structure of the country. They did serve, however, to furnish that indipensable prerequisite to geological research, a base map on which to present the geographic relations of the facts. From the Jesuits down to Pumpelly's day certain diplomatic missions had been permitted to traverse the interior, and it had not failed that botanists and zoologists had in a few instances penetrated the land; but such journeys were undertaken only by special permission or at very great personal risk.

From 1860 to 1862 there had been in China a German diplomatic mission, attached to which was a young geologist, Ferdinand von Richthofen, who was eager to explore. He found the conditions so unfavorable, however, that he confined his movements to the coast. Completely thwarted in his efforts, he visited the East Indies and finally crossed the Pacific to California, where he remained until 1868. He had then developed a plan for a systematic exploration of the Chinese Empire and, backed by Professor Whitney, he secured funds for an expedition from the Bank of California. Returning to China, he entered upon his task, to which during four years he devoted all his energies, with the result that his name, Von Richthofen, is identified in the annals of science with the unveiling of the "Middle Kingdom." His researches into the physical geography and geology of the country continued throughout his life, and he left a third volume of his great work, "China," unpublished at the time of his death, in 1905.

In 1863, after Richthofen had left for California, Pumpelly arrived in Shanghai, where he remained some weeks. Seeing on the Yangtze river a boatload of excellent coal from far in the interior, he was seized by a longing to explore. In his "Reminiscences" he says:

> "Excepting missionaries, few travelers had penetrated far into the interior. Huc had descended the Yangtze from Tibet. Blakeston had described that river. The geology of the Empire was absolutely unknown, for Richthofen had not yet undertaken his monumental work. So here, as in Corsica, yielding to the call of the unknown, I engaged passage on the steamer *Surprise*, bound for Hankow, the end of steam navigation up the Yangtze."

Thus, like a boy starting on a pleasure trip, Pumpelly struck out into a country devastated by nine years of rebellion and scarcely less lawless,

so far as foreigners were concerned, than the Arizona from which he had so recently escaped. He was not in search of adventure. Danger was merely incidental to satisfying that interest he felt in the strange people and their unknown land. But neither did danger deter him, either out of regard for his safety or because it would interfere with the attainment of that knowledge which he sought. In this latter respect he differed from Richthofen.

It is interesting to contrast these two great explorers, who had so much in common, yet pursued their ends so differently. It was the writer's privilege to know them both. They were equally bold in conceiving their plans, equally broad in their interests in the Chinese as a people and in China as a land. They differed radically, however, in their ultimate purposes. Pumpelly sought knowledge for knowledge's sake. He wished to know the as yet unknown, but he felt no impelling desire to inform others, nor any special obligation to do so. In his generosity he gave as freely of his thoughts as of things material and always with the desire that others should derive the greatest possible benefit from the intellectual largesse that he scattered so liberally. It might contain the seed of a vital contribution to science; he who could cultivate it was welcome to the reward of its harvest. With Richthofen it was otherwise. He was a guardian of learning. He felt responsible for it. In its pursuit he was farsighted, systematic, patient, and persistent. What he acquired he cultivated. His harvest he shared with those whom he deemed worthy. To do so and to welcome any contribution of fact or of right inference, these were part of the obligation laid on him by his station and his standing.

The difference between the two was temperamental and not merely individual, but racial. Pumpelly derived from the roving Vikings, happiest when driving care-free down the winds of opportunity beyond the ken of men. Richthofen was a modern Roman, obedient to the system in which he had been drilled and of which he knew himself to be a leading exponent. They typify the spirits of America and Prussia.

Pumpelly's excursions in China were limited as compared with Richthofen's journeys. He did not wait for favorable conditions, but even he, when low with fever, could be turned back by a Chinese mob. Thus it happened that he and his companion, the Rev. Josiah Cox, cut their houseboat adrift before the charge of thirty thousand and abandoned the examination of the coal fields of Hunan, the province in which the natives were most violently opposed to foreigners. They were not deterred, however, from proceeding on their voyage up the Yangtze, which they ascended to the head of the Lower Gorges. Pumpelly was deeply

impressed by the superb scenery, where the huge river coils through the narrow pass between towering cliffs of limestone. He watched with intense interest the progress made by a hundred and fifty coolies, who dragged the junk up against the tumultuous current, as had been the custom for thousands of years. He probably felt a thrill not unmixed with delight when the bamboo ropes parted and they went swirling downstream, for who could know what would happen next?

Eight days were required to warp up through the Gorges, and Pumpelly observed the vast arch in which the strata, that at Ichang emerge from under the plain of the Yangtze, rise and descend again, after arching to such a height that the underlying granite is exposed in the center. The axis of this arch, or anticline, trends northeast-southwest, as Pumpelly noted. Subsequently he connected it with the marginal ranges of the Mongolian plateau and other features having the same trend and thus identified a major structural feature of the Asiatic continent. He gave it the name of "Sinian" trend or axis, from the ancient Hebrew name *Sinim* for China. He thus recognized and named one of the cornerstones of the geology of Asia, both the structure and the name having been accepted by all later observers.

The limestone formation which constitutes the walls of the gorges impressed Pumpelly with its extraordinary thickness. The grandeur of the cliffs suggested the vastness of the seas in which the strata had been deposited and made an impression that influenced his views on the area covered by it. He estimated the thickness of it at 11,600 feet. It has since been determined to be about 8,800 feet, including a parting of shale. He found no fossils, but thought that certain Devonian forms which had been identified from China must represent it, and therefore assigned the entire thickness to that period. We now know that the lower part belongs to the Cambrian and Ordovician ages, while the upper limestone pertains to the Carboniferous.

The recognition of the Sinian trends and the assumption of a widespread Devonian limestone gave a clue to the general structure of China, which Pumpelly embodied in the first geological map of the empire ever attempted. Beneath the "Devonian" limestone he grouped all the rocks in a "granito-metamorphic series." The Coal Measures he placed in the Triassic on the evidence of plants identified for him by Newberry. The alluvium of the eastern plains he assigned to the "Tertiary and post-Tertiary." He traced the distribution of these few formations by the occurrence of characteristic minerals, as reported to him by Chinese scholars whom he employed to search the records for that purpose. Thus he expanded his own meager observations to a sketch which, if necessarily

erroneous in many ways, nevertheless contains a large proportion of correct inference.

In turning to Chinese records for information regarding the distribution of mineral resources, Pumpelly was not deterred by the volume of the material, which was enormous, nor by his ignorance of the language. He found natives to glean the scanty data from the huge volumes of ancient and recent writings and missionaries to translate them. It was a characteristic effort, due rather to his German training than to any personal inclination toward exhaustive research, but one which was frequently repeated in the course of his career. He appreciated the value of details, even though he himself would only reluctantly go through the drudgery of digging them up. He willingly left to others both the labor and the credit. Van Hise, a master of detail, whose volumes outbulk Pumpelly's writings a thousand to one, presents an interesting contrast. He also employed others to work with him, but very differently. Meticulously accurate and systematic, he planned his work far in advance, estimated his own ability to execute the more essential part, and availed himself of the aid necessary to secure completion within the allotted time. Single in purpose, he completed each task according to a preconceived plan. Pumpelly, on the other hand, conceived a fruitful thought as lightly as a boy sees a vision in the sunrise, as lightly he gave it wing, and he was happy if another thought it worthy of attention. He congratulated himself that there were others trained and more than willing to follow out the lines of investigation which he spontaneously suggested, leaving him free to turn to any one of the manifold interests which claimed him.

Pumpelly's journeys in China during the autumn of 1863 were accomplished under official escort in search of coal for naval use. They served to broaden his understanding of the relations of the Coal Measures with the great limestone formation and gave him the foundation upon which he expanded his observations in the Yangtze Valley to northern China. They also afforded him material for amusing chapters in *Across America and Asia*. He spent 1864 partly in China, partly in Japan, and in November of that year started to return to America by crossing Mongolia and Siberia to Europe. On this journey he made those observations of the inland basins of Asia and of the disintegration of rocks in an arid climate which appeared subsequently in his theory of the loess as a lacustrine deposit.

In his scientific contributions to the geology of Asia, Pumpelly apologizes for the often meager results on the ground that the expeditions were carried out with private funds and were attended with difficulties

due to the hostility of the natives. He also mentions the intense cold of a winter journey across the plateaus of Tibet as a limitation to geologic observation. To these we may add the very inadequate state of geologic knowledge and theory when considered as a key to the problems he had to face. Thus he reasoned regarding the origin of the rock-rimmed basins of central Asia. Having no outlet, they could not be stream-eroded valleys. Wind, however, was an obvious eroding agent which could excavate basins, and so he attributed to the wind effects whose magnitude surpasses its reasonable activities. There was then no hint of the physiographic clue by means of which we have since learned that the surfaces of the continents, and notably of Asia, have been warped recently in a way which gives rise to wide depressions as well as to broad plateaus.

He recognized that the Yellow River in its north-south course, before it turns east toward the plains, follows an unusual channel across east-west mountains, but since science knew nothing of the changes which may be imposed on a river by stream-capture, he sought an explanation in a catastrophe, an upheaval, of which he found suggestions in very ancient Chinese traditions.

He was impressed by the enormously wide distribution and thickness of the fine-grained loess deposits and, following the accepted theory of lacustrine origin, he postulated the former existence of extensive lakes. Thus he reasoned according to the state of theory at that time, and failed to find the correct solution of the problems because they were beyond the reach of contemporary understanding; but he grasped the problems.

Lake Superior, 1865 to 1877

Upon his return to America in 1865, Pumpelly encountered the changes wrought by the Civil War. With the exception of what may be called a brief visit to his home in 1860, he had been away sixteen years—years of growth from boyhood to maturity for any man and for him years of extraordinary experience. Writing of it fifty years later, he refers to the desultory character of his schooling, comprised in the preparation for Yale and three years at Freiberg, and stresses the value of that broader education which flows from intercourse with the world:

"One can not in young manhood be in more or less intimate and confidential and unprejudiced association with men and women of many peoples without getting some insight into the complexity of human nature, into the relation of virtues and weaknesses to subconscious motive forces. Such experience makes for introspection and charity.

"I had learned also the sameness of the fundamentals of human nature,

whether evident on the surface in the savage, or veiled by conventional restraint in civilization, or again in the white man when unrestrained beyond civilized environment. I had employed men of many kinds and races—Corsican mountaineers, Indians, Mexicans, white men (both normal and outlaw), Japanese, Chinese, and Mongolians—and had learned to understand racial character well enough to get on smoothly. In Japan, in official position, under the feudal régime, I had established intimate, in some cases affectionate, relations with my staff of Samurai officers. In extended travels in China my experience had ranged from the receipt of courteous hospitality to the necessity of turning a hostile mob into a friendly one.

"In commercial Shanghai I had seen the causes of dislike of the foreigner. In Peking I had purposely been allowed to see at first hand the attempts of a broad diplomacy intended to remove those causes. And as the head of an Imperial Chinese commission consisting of civil and military mandarins, I had come in contact with local magistrates and had seen something of Chinese character in dealings of the central government with the local democracy.

"I had seen nature in all its aspects, of mountain and desert and cultivation, between the tropical and Arctic circles, and its corresponding influences on man and civilization.

"These were some of the factors in my deeper education up to my twenty-eighth year. If I had been conscious of the fact that I was going through a great school, I should undoubtedly have profited vastly more than I did. However, in its gradual growth that school had helped me through dangerous or delicate situations, and had moved me to give weight to the better instincts of men of all races when those instincts are properly appealed to. It had developed in me a racial sympathy and made clear the dangers of racial prejudice."

Thus, before reaching the age of thirty, but a third of his life gone by, Pumpelly had graduated from the school of human nature with the degree of *advocate of tolerance*. He is a rare exception to the rule that most men never enter that school understandingly and few get beyond its most elementary lessons, however long they may live. Those who attain to his degree are apostles of the millennium.

The Civil War left a number of men in the prime of life accustomed to danger, initiative, and large undertakings. A post-war period is intensely stimulating when the exhaustion of resources has not gone too far, and in the United States the vast wealth native to the country was scarcely touched. It was an environment in which Pumpelly found many congenial friends and opportunities for the exercise of his special gifts and training. He did not immediately enter upon the practice of his profession, but gave himself up to the enjoyment of society, where his personal charm, his geniality, and his broad knowledge made him universally welcome, and to the writing of his two books, "Across

America and Asia" and "Geological Researches in China, Mongolia, and Japan."

He became closely associated with Whitney, whom he had known in California, and through him he was invited to accept the Chair of Mining at Harvard under the Sturgis-Hooper Endowment. As the available income would not suffice to pay him a professor's salary, Pumpelly accepted; his duties would be light and he would have much freedom. He is therefore listed as having been a professor at Harvard, but he never entered seriously upon the work of teaching in the university. Inspiring as he was as an instructor in the presence of Nature, he was ill fitted for systematic teaching in an institution.

In the summer of 1866 Pumpelly made a first excursion to Lake Superior to report on a copper property, and became acquainted with the possibilities offered by exploration of the iron ore ranges as well. He was by nature a prospector, and here was a prospector's chance, upon which he prepared to embark, risking his own and his brother's resources. But, given an opportunity to locate a floating land grant, he was enabled to do justice to his employers while at the same time he studied the conditions of occurrence of the iron ores and became acquainted with lands they could not acquire. Thus left free to exercise the right of second choice, he threw himself into the exploration with the definite purpose of investing his savings in timber and iron lands. At this time he became acquainted with Major T. B. Brooks, who had already worked out the geology of the Marquette iron district, and the two entered into an informal association, which lasted without any written contract for nearly forty years. Confiding each in the other, they invested from time to time such funds as each could individually spare in lands that one or the other of them might select.

Brooks was a self-made engineer and geologist, who by force of character, ability, and indomitable energy had developed himself from a farmer's boy to the position of vice-president and general manager of the Clifton iron mine on the practical side and in the scientific world to that of the leading authority on the geology of the iron deposits. He was a year older than Pumpelly—that is, just thirty—when they met; but, having spent three years under the stern discipline of war and possessing a far more exacting habit of life, he seemed much older by comparison. The two men came together on the common ground of their interest in exploration with both practical and scientific objects in view. They became united by bonds of mutual respect and confidence, which were never broken. Their families came into relations of intimacy. Yet there must ever have remained in each a phase with which the other

could not readily sympathize. Brooks was intensely practical, definite, and devoted to the business in hand. Pumpelly was habitually impatient of details, eager to be done with them, so that he might be free to roam in any one of the intellectual fields so attractive to his brilliant mind. Ten years later the writer received his earliest training in field-work from these two geologists. Brooks might have been a father, Pumpelly Phœbus Apollo.

The State of Michigan was fortunate at this time, when the exploitation of its resources was just beginning, to have two such men as Brooks and Pumpelly interested in that development. They accepted the tasks of surveying the iron and copper districts and laid sound geological foundations for prospecting and mining. The insignificant appropriation made by the State was inadequate even for expenses. The investigations were thus a gift to the Commonwealth as well as to science.

Pumpelly undertook the study of the copper deposits. The limitations of the work required that he should decide between a general reconnaissance of the forested and drift-covered area or limited but accurate observations of certain sections and deposits. In contrast to what one might have expected, he chose the latter, rightly judging that specific information regarding the stratigraphy and conditions of mineralization of the copper-bearing rocks would be of more value than loose generalizations, such as had characterized the exploratory work of his predecessors. The problem was one for which his German training had prepared him advantageously.

Delegating the measurement of sections across the series of strata to his assistant, Marvine, he himself undertook the investigation of the broader stratigraphic relations, especially those of the bedded copper-bearing sandstones and volcanics with the Cambrian, which had been described as conformable. This required field observations of a kind in which we might expect him to excel, as he did—observations demanding the correlation of facts assembled from a wide area and interpreted with keen perception of their relative value and significance. He recognized the now well-known unconformity between the Keweenawan and Cambrian sandstones and published jointly with Brooks an article on the age of the copper-bearing rocks.

Pumpelly's major contribution to the study of the copper deposits reminds one of Breithaupt, his instructor in crystallography. Seeking the conditions under which the native copper had been deposited in association with quartz, epidote, prehnite, calcite, and other minerals, he examined under the microscope hundreds of thin-sections, which he ground himself, measured the angles of microscopic crystals, and distinguished

the older from the younger minerals by the interpenetration of one by another or by the forms assumed by pseudomorphs. He thus determined the paragenesis of the copper and traced its reduction to the metallic state through the chemical reactions with ferrous minerals present in the associated rocks. He attributed the concentration of the metal to descending surface waters. In this he followed Whitney and has been followed by Wadsworth. Van Hise was of the opinion that ascending waters had brought in the copper, but this is not sustained by the evidence, according to Lindgren. In identifying the copper as indigenous to the series of rocks in which it occurs, Pumpelly thought it to have been derived originally from seawater. Van Hise later called attention to the widespread occurrence of it in the Keweenawan traps and looked on the lavas as the source. Lane has suggested that the submarine outflow of the lavas gave rise to reactions with the seawater, which led to the reduction of the copper. This is a modification of Pumpelly's idea, which postulates ferrous oxide as the reducing agent. Exhaustive research has thus to some extent supplemented or modified the views of the pioneer in this field, but the body of fact and inference which he assembled remains the accepted truth. The surprising thing to one who has followed his adventurous career through Arizona and Asia is that he could patiently devote himself to tedious microscopic studies with such success. He began his work on the copper deposits in 1870 and his last paper on the subject, "Metasomatic development of the copper-bearing rocks of Lake Superior," was finished in 1877.

Pumpelly's work on the Lake Superior copper deposits would present no novelty if carried out today, when the processes of metamorphism have become familiar to all students of ore deposits, but they constituted an original contribution of very great value fifty years ago. Among those who then came under his influence was Waldemar Lindgren, at the time just entering on that career in economic geology in which he has rendered such valuable service to science and mining. He, like Pumpelly, was a graduate of Freiberg and, of Swedish birth, had recently come from Europe when he entered the Transcontinental Survey. He writes:[3]

"I first met Pumpelly in November, 1883, and remained in his office at Newport until February, working during that time on thin-sections of rocks obtained during the field-work of the Transcontinental Survey in the summer of 1883. I was tremendously impressed, both by his knowledge and personality, and I shall always remember his kindness to me, at that time a recent graduate from the schools. His advice on petrographic work was extremely

[3] Personal communication.

helpful, but I was not then acquainted with his epoch-making work on the minerals of the Lake Superior district. As I began to dip into metasomatism later on, I soon found that he was really a pioneer in the study of changes which minerals undergo. Of course, this matter had been discussed previously by Naumann, Blum, and others in Germany and elsewhere in Europe, but Pumpelly was the first to apply the microscope to these problems. He was probably the first one in this country who undertook petrographic examinations by using thin-sections. Neither the microscopes nor the sections were as good as they are now, but it remains as a great credit to his genius that the conclusions he arrived at stand, with minor exceptions, practically unchanged today. His work showed great originality, and in this direction of the microscopic study of minerals he was as much of a pioneer as he proved to be in geological explorations. Our geology of today certainly owes a great deal to his pioneering work."

Thus Pumpelly opened up a new line of research in this country, one which has proved a mine of wealth in a material as well as scientific sense. His ideas are reflected in Brooks's early suggestion of the secondary origin of the Lake Superior iron ores, fully developed and established later by Van Hise, and they have borne fruit in the comprehensive studies of secondary enrichment which characterize the investigations of ore deposits during the last two or three decades.

Missouri, 1871 and 1872

Appointed State Geologist of Missouri in the autumn of 1871, Pumpelly took up the task with the intention of remaining in the official position only as long as might be necessary to study the geology and distribution of the iron ores of the State and to prepare the way for a systematic study of the other mineral resources. Being taken seriously ill after a year in office, he resigned in the winter of 1872-1873. His contribution to geology during this eighteen months is comprised in the report of the Geological Survey of Missouri for 1872. He himself wrote only on the geology of Pilot Knob and vicinity and he confined himself to a description of the occurrences and kinds of the iron and manganese ores. It was a preliminary, perhaps, to a systematic study of their origin, but if so it was never carried further. In resigning, Pumpelly left a good working organization, which was taken over and carried on by his successor, G. C. Broadhead.

Loess and secular Disintegration, 1863 and 1876

Earlier in this memoir reference has been made to Pumpelly's observations of the widespread deposits of loess in China and central Asia, which he explained as of aqueous sedimentary origin, consisting of glacial mud

laid down in a chain of lakes. It was not known in 1863 that northern Asia had not been extensively glaciated, and the topography of the continent had not been mapped with sufficient detail to render improbable the former existence of great lakes. Richthofen's extended journeys gave him a better opportunity to observe the extraordinary facts of the distribution of Chinese loess and led him to the correct hypothesis of its carriage and deposition by wind.

The origin of the material of which loess consists Richthofen sought in the disintegration of rocks under changes of temperature and in wind erosion of soft desert formations rather than in glacial erosion, as Pumpelly had done.

But both of them in their earlier thought had failed to recognize that the processes of grinding or disintegration are far too slow to keep pace with the transportation of loess. The current local supply would be exhausted and loess accumulation would cease long before quantities such as exist could possibly be assembled. Pumpelly, reviewing Richthofen's work in 1876, recognized this weakness in the former's hypothesis of loess origin. While he accepted the revision of his own ideas and indorsed as correct Richthofen's theory of transportation and deposition by wind, he brought his observation of the deep decay of rocks in moist climates to bear on the problem of original supply and supplemented the theory at a vital point. He also extended his idea to the origin of ice-transported material. We may best quote his own words from his "Reminiscences" (page 612). He says:

"My argument was:

"(1) That during long ages of normally moist climate the rocks of a region become disintegrated and decomposed often to great depths. This is evident in all regions that have not been denuded by glacial action.

"(2) That any climatic change that permanently destroys the vegetation leaves the disintegrated mass a prey to forces of transportation.

"(3) Through a climatic change causing a glacial period there would come the removal of the altered rock-mass in all the forms of glacial débris—boulders, gravel, clay, and glacial flour, which is the product of the grinding of débris and rock bed under the moving ice. This material is in part left by the retreating glacier as moraine and glacial drift or till, and in part is carried as coarser or finer débris by streams to be spread over the lowlands or carried to the sea. The downward disintegration acting on rocks of different power of resistance would leave an abnormally irregular topography of the solid rock surface in which depressions scoured out by the loaded ice would remain as rock basins.

"(4) If the change is to aridity, the region becomes a desert, vegetation disappears, and the disintegrated rock-mass becomes prey to the winds.

"In Asia the products of glacier work were spread out to dry on the flood-plains of rivers emerging onto the deserts. Thus water had played an

intermediate part in the origin of a portion of the loess. But the final stage of its transportation was, as shown by Richthofen, by the winds that sifted it out from the sands and carried it beyond the barren desert to find rest in the grass, which protected it and which it nourished. Richthofen accepted my view and published it with credit in his second volume."

Here was a broad deduction, based on extended observation and carried to its logical consequences. It embraced the concepts of changing climates, altered conditions of erosion by ice, wind, or water, varied results in sedimentation, and the effect of modified environment on organisms. In Pumpelly's presentation before the National Academy of Sciences he touched upon each of these aspects of the subject and demonstrated his grasp of them. Yet he did not follow them further, did not develop the lines of investigation which radiate from this central group of ideas.

Another great mind, a contemporary of his, similarly brought face to face with the problem of climatic change, pursued its ramifications till led to a new theory of cosmogony. His was the mind of a profound and philosophic thinker. Pumpelly's was that of the explorer in the realm of thought as in that of observation. He glimpsed a truth; he described what he saw from the mountain top; he did not descend to launch his thought on an eddying current; he had no impulse to survey in detail the scenes among which he would not permanently abide.

Yet his argument rounded out the suggestions of other geologists and introduced the climatic factor as an essential element of reasoning regarding the processes of evolution of physiographic features, continental or marine sediments, and the development of organisms, including man and his civilization. In this last-named relation Pumpelly long afterward showed the importance of the climatic factor in his investigations of the ancient cities of central Asia.

Official Surveys, 1879 to 1890

Pumpelly was now forty years of age. He had behind him the experience and observations of an ordinarily full life. Although at times hard pressed for immediate moneys, for he was a generous and care-free spender, he had from his student days up been accustomed to alternating fulness and emptiness of purse, and its condition never long affected his habit of living. He was happily married; he had hosts of friends with whom he shared a variety of interests. Science, literature, history, art, development of national resources, farming, social opportunities—all drew out his abundant interest, gave outlet to his exuberant vitality.

Under these circumstances he was naturally invited to take part in the

larger enterprises in which geology was a factor, not as an investigator, but as an organizer.

The consolidation of the Government surveys of the Far West under the leadership of Clarence King and the plans which the Survey developed in connection with the taking of the Tenth Census gave Pumpelly an opportunity. He accepted the responsibility for the census of the mineral industries, exclusive of the precious metals and petroleum, and directed the forces at his disposal toward a complete investigation of the geology and chemical nature of the iron ores of the country, at least in the more settled regions. This purpose was a natural outcome of his world-wide knowledge of the bases of civilization and his intimate studies of the iron deposits of Lake Superior and Missouri. He fully realized that the future of American industries was involved in the production of iron and steel in competition with the world. He appreciated the need of more thorough knowledge of the distribution of good ores. His mind daringly hurdled the difficulties of so great a task and he confidently organized his division, with very inadequate resources in men and money, it must be confessed.

Four young geologists were sent into the field equipped with the title of "special expert," the humor of which the writer, at least, who was of the number, was too inexperienced to appreciate. A group of chemists was gathered at headquarters, in Newport, Rhode Island. During two years, 1879 to 1881, the field men diligently sought out the iron ore occurrences of the States east of the Great Plains, many of them known only through the tradition of a colonial charcoal furnace. Each occurrence was described as found and any available ore was sampled as carefully as the circumstances permitted. In the case of working mines or stock piles, the method of quartering down large samples composed of many bits of ore taken at random was employed; in the case of an abandoned ore bank, such material as was on the surface was taken. There was no excavating. The observation of geologic associations had to be superficial. Nevertheless, the amount of information gathered, comprising the description of localities and the chemical analyses of more than a thousand ore deposits, constitutes an important contribution to our knowledge of the national resources in this important metal. Pumpelly's share in it lies in the initiative, in the working out of a practical plan within the limited appropriation, and particularly in the inspiration he gave to his assistants. In his "Reminiscences" he refers appreciatively to the *esprit de corps* which ruled throughout the organization. The thrill of it persists after more than forty years. Its source was in his

own abounding enthusiasm and generous confidence in the loyalty and capacity of the young men whom he drew about him.

In 1881, before the Census work was completed, Pumpelly was offered an opportunity than which none could have been better suited to his tastes and abilities. Mr. Henry Villard, president of the newly reorganized Northern Pacific Railway, with rare foresight, realized that the exploitation of the vast empire across which the road was being built would proceed far more advantageously if guided by knowledge of the resources of the region. He appreciated, furthermore, the need of basing that knowledge on facts rather than on hearsay, and he understood that facts can best be assembled by trained observers. He proposed, therefore, the organization of an economic survey, which was to cover the freight resources tributary to his road and which should rest upon studies of the geology, soils, and timber lands. He invited Pumpelly to become its director.

With what enthusiasm that invitation was accepted can be understood only by one who knew Pumpelly's interest in great, beneficent enterprises of a practical character. He was a man of very broad, far-seeing vision. So was Henry Villard, though from another angle. Their two minds worked sympathetically. Here was a vast realm of great potentialities; here were almost limitless plains and mountains, under varied climates, to be opened to human settlement; here were resources of all kinds to be exploited in the building up of new communities; the railway, stretching out under Villard's direction, was to be the instrument and Pumpelly's survey the guiding intelligence of this illimitable enterprise.

It was born too big to live long. The Northern Transcontinental Survey, as it was called, demanded expenditures commensurate with its scope. Mr. Villard supported it most liberally while his power lasted; but when, after three years of intense activity, he failed, just as the rails were linked from terminus to terminus, the Survey fell with him.

We are not here concerned with the causes of the failure, which are to be sought in the rivalries of kings of finance for the control of empires; but it is but doing justice to two able, practical men to record the fact that the Transcontinental Survey far more than paid for itself. It may fairly be estimated that it saved its cost in checking the extortion which was being practiced by officials of the road upon the company (through the reselling of lands privately purchased by them or their friends) and in coal lands that were discovered by the geologists of the Survey and acquired by the Land Department of the railway it has paid for itself many times over, with compound interest on the investment.

Pumpelly threw himself into the work with optimistic energy. In his "Reminiscences" he states that he divided his personal supervision between administrative work and reconnaissance expeditions, to get the broad conceptions of the problems necessary to blocking out plans. His capacity in administration was shown chiefly in selecting his assistants, nearly all of them young men, to whom he gave generously of confidence and freedom of action—an excellent method when the initial choice has been wisely made. His personal direction of the work was limited to brief instructions, commonly given orally, and to occasional visits of a day or two, devoted to rapid reconnaissances of the fields under survey. He trusted us (I speak for my comrades, most of whom have preceded their great chief on the long trail) and he received the response which youth ever gives to faith associated with enthusiasm.

The winters of 1882, 1883, and 1884 were spent by the entire technical force at headquarters, at Newport, Rhode Island, where the younger members enjoyed frequent contact with the director and learned much from his world-wide experience. Pumpelly spent the summers of 1882 and 1883 in Montana and the Rocky Mountains of Idaho. He made two attempts to cross the latter, from the Plains to the Flathead Valley, by way of Two Medicine Pass, from which he had to turn back on account of deep snow, and more successfully by the Cutbank Pass. The latter trip led him across what is now the southern part of Glacier National Park and he first saw the glaciers at the head of Thompson Creek. It does not appear that he made any notable geological observations on any of these excursions. His contributions to science were made through his assistants, who were encouraged to prepare their results for publication over their own names, even after the failure of the Northern Pacific had cut off all support from that source. How the staff was kept at work and paid during the winter of 1884 has never been divulged, but it is a fair assumption that Pumpelly backed his determination to get out the results without regard to the cost to himself. The geology of the coal fields, which had been studied in Montana and Washington, was published in the volume issued by the Tenth Census, Number XV, containing the results of the Census studies, also made under Pumpelly's direction.

Green Mountain Studies

Detailed investigations, requiring painstaking application in field or laboratory, were foreign to Pumpelly's free, roving nature, yet his German training had taught him the value of intensive studies and he showed himself capable of executing them, as in the examination of the

Lake Superior copper deposits. Accident rather than design threw some of the most difficult of American geologic problems in his path. In association with Irving and Van Hise, he studied the pre-Cambrian, and later, as geologist in charge of the New England Division of the United States Geological Survey, he directed the surveys of the Green Mountains of New England, more particularly with reference to Hoosac and Greylock Mountains.

His contributions to the solution of the pre-Cambrian problems, involving the metamorphism, structure, and original character of the ancient crystalline rocks, were made in conversation in the field face to face with the facts or in talks of an evening between days' work. They were not recorded, but his colleagues, notably Van Hise, have borne witness to the value of his penetrating insight into the intricate relations and processes.

Pumpelly greatly enjoyed his association with Van Hise, especially in excursions which he made with him in conference on pre-Cambrian studies of the Appalachian Mountains. This brings to mind a day on the French Broad River, in North Carolina, where the two geologists invited the writer to accompany them, it being at the time his immediate field of work. The section examined comprised the base of the quartzites, which Keith has since determined to be Cambrian, and the underlying granites. There is a stretch of perhaps two hundred yards in which the obvious granite grades into the distinctly stratified quartzite, but in which no plane of contact can be recognized. After passing carefully over the section a couple of times together, the two separated.

Van Hise had begun to collect a series of specimens which should show the mineralogical character of the crystalline and sedimentary rocks and of the transition zone. He was thinking of the metamorphism, which according to hypothesis had altered an arkose sediment into something closely resembling the parent granite, and was considering the distinctive criteria which might be looked for under the microscope. He afterwards published papers on the secondary enlargement of crystals, in which these specimens played a part.

Pumpelly had turned to look at the tossing river and the beauties of the gorge. He spoke of the exhilaration of the scene, contrasted it with a desert landscape of granite hills and enveloping sands, which he made very real by a few graphic touches, outlined the process of disintegration which granite suffers under those conditions, and left it rather to be understood than stated, that the relations we had just been observing, in reminding him of the deserts of Arizona or central Asia, had suggested the aspects of the Appalachian region in a long past geologic age.

Each thinker followed his inherited lines of reasoning. Van Hise was adding a few precisely observed facts to that enormous mass of details upon which he based his thorough analysis of the most difficult problems of American geology, those of the pre-Cambrian. Pumpelly saw the facts, readily interpreted them in terms of known processes, drew an analogy with scenes he knew, and swept up on the wings of imagination to heights from which he could cast a glance down the long vista of the past.

It was with a penetrating understanding of the relation between sediments and the geographic or climatic conditions which govern their character and distribution that Pumpelly directed the investigation of the Green Mountains of New England. The general facts of stratigraphy and structure had been observed by the two Hitchcocks, Ebenezer, Emmons, Hall, J. D. Dana, and other contributors to the Taconic controversy. Each had espoused an idea and advocated it, but of precise observation and rational interpretation the very controversy itself had proved the need. Pumpelly took but little account of all that had been written. He went back to Nature's record. Having selected a critical area comprising Hoosac Mountain, an anticlinal ridge with a granitoid core, and Greylock Mountain, a synclinorium, he with his assistants, Wolff and Putnam, Dale and Hobbs, traced out in great detail the areal and structural relations of the granite, gneisses, schists, and limestones of which the geologic column is composed. Any careful observer might have done as much, but there remained several outstanding riddles that could be solved only by that use of the imagination which with Pumpelly was intuitive rather than deliberate.

Running through the sediments and gneisses and fading out into the granitoid rocks was an appearance of bedding which had been interpreted as such and had led to the opinion that the different rocks all belonged to a conformable series. Wolff and Dale, guided by Pumpelly, proved it to be a secondary schistosity, and thus disposed of the apparent conformity. The actual unconformity of the Cambrian sediments on the pre-Cambrian was then demonstrated by evidence of weathering of the older rocks in pre-Cambrian time, especially where a dike occurred in the granite, and the deposition of clastic sediments in the irregularities of the old land surface. Metamorphism had greatly obscured the original character of the sediments, some of which had been altered to gneisses, and Pumpelly credits Wolff with having carried out the tedious field and laboratory investigations required to establish the true relations. It may be noted that both chief and assistant were trained in exact

German methods, the one in mineralogy and structure, the other as a modern petrographer.

In the study of the Cambrian stratigraphy, which was obscured by schistocity, the true sequence of the strata could be ascertained only by the identification of obscure anticlinal or synclinal folds, where the dips are closely or actually isoclinal. Here the application of principles published by Heim in his "Mechanics of Mountain Building" was of critical value and Dale worked out a group of American examples of the laws originally recognized in Switzerland. These are today classical illustrations of the structures to be looked for in metamorphosed sediments.

A further problem presented itself in the differences of sequences of sedimentary beds in Mount Greylock and in Hoosac Mountain. In the former the Cambrian strata comprise both limestones and schists; in the latter there is only a great thickness of schists, both sections rising from the basal quartzite. The lack of agreement across the short span between the two ranges had been explained by the assumption of a fault, but Pumpelly and his assistants proved that there was no fault and solved the riddle by demonstrating that the strata in Hoosac Mountain are the near-shore equivalents of the offshore deposits which form Greylock.

It is the old story of Columbus's egg. The monograph on the Green Mountains has taken its place among the accepted results of geological research. The hypotheses have become part of the rationale of working geologists. We take for granted the penetrating insight into past geographic conditions, the understanding of obscure processes, the capacity for patient, conclusive investigation, those qualities which enabled Pumpelly to open a new era in the geology of New England and to settle a controversy which had lasted for half a century. It is as it should be. The perfect stone has found its place in the great structure of geologic science.

The elucidation of the problems of the Green Mountains was Pumpelly's last contribution to his adopted science, geology. In 1890, after six years of Government service, during which he had perforce given up the remunerative practice of his profession, he shared the lot of the scientists who work under official limitations. He was poor. The owner of large areas of iron lands, he saw their potential value being eaten up by taxes. Business conditions were such that there was little opportunity to recoup his fortunes through expert examinations of mining properties. He had a considerable family, led by himself in habits of lavish liberality. Under these adverse conditions, in 1893, he took his family abroad and during two years set his children an example of economy (so he says in

his "Reminiscences"). They traveled much in Italy, France, and Switzerland. One can imagine the mutual delight of their companionship among the scenes of the father's youth. Returning home in 1895, Pumpelly once more took up the practice of his profession, but, finding the opportunities few, he renewed his explorations of the Lake Superior iron ore districts. These efforts were, however, not particularly successful in the discovery of valuable ore deposits.

The years passed in home life among his growing children and in excursions to the Far West or to Mexico to make mine examinations, but in 1903, at the age of 66, he was once more seized with the desire to explore distant lands.

Explorations in Central Asia, 1903 to 1904

For forty years there had lain in Pumpelly's mind a spark, originally lighted by his imagination, which required but a breath to kindle it into flame. The central thought was the relation of climatic changes in central Asia to the migrations of peoples and the evolution of civilizations. In it were combined the fragmentary suggestions of Chinese history regarding ancient cities and peoples and the deductions from geographic and geologic evidence, which sufficed to give color to the hypothesis of a changing climate.

The spark was kindled by a fact recorded by an ancient Chinese mapmaker, who inscribed the words "Here dwell the Usun, a people with red hair and blue eyes," on a map of the Tarim basin, in Chinese Turkestan, at a point apparently north of Kashgar. Another record mentioned the fact that many cities had been buried by advancing sand nearly two thousand years ago. These notes were brought to the attention of Pumpelly by the Chinese scholars employed by him during his stay in China in 1862-1863. He then felt that he was on the track of the ancestors of the European races (one can not help thinking how accurately the description fitted him, himself), and, pursuing a line of reasoning suggested by the diminishing inland lakes without outlets, he attributed the migrations of these peoples to a desiccation of the climate of central Asia. This hypothesis, since elaborated by Huntington, who was one of his assistants in 1903, lay for forty years in its author's mind, withheld from development by that scientific caution which had prevented him, when but a boy, from publishing his idea of an inland sea covering the Sahara.

The Chinese records and the facts he observed in his journey across Siberia in 1863 had suggested the idea of the former existence of an

inland sea in the now desert regions of Asia, and subsequent speculation had connected the sea with the Glacial Period, while its shrinkage would naturally follow from the waning of the conditions that had caused glaciation. But this logical chain of ideas lacked confirmatory evidence until Pumpelly was told by the Russian geologist, Tchernyscheff, that strata containing shells of the Glacial Period had been found in a position that seemed to indicate an inland sea of that time. The "dream," as he called it, then assumed the form of legitimate hypothesis, worthy of being tested. It had previously seemed to him through all those years, during which he had discussed it with scientific friends, too subjective in character.

Furnished with a grant of funds by the Carnegie Institution of Washington, Pumpelly carried out two expeditions to Turkestan, one in 1903, to reconnoiter the country and seek for the evidences of geologic changes in association with those of ancient civilizations; the other in 1904, to excavate old dwelling sites. In the organization of these expeditions he was guided by the experience of a lifetime of travel and aided by the prestige of the Institution he represented, as well as by his own great reputation. He chose as assistants specialists distinguished in physiography and archeology and, as was his custom, gave them free rein in their investigations, together with the fullest possible opportunity to publish their results as their own.

The purpose of the expeditions was chiefly ethnological, as the dream had been. In his youth Pumpelly had been divided in his interest between history and geology. Chance had directed the emphasis of his training to geology, but he had always shown a profound, if not a preferential, interest in his fellow-men and their development. Now the earth-science stepped into the background. He assigned to W. M. Davis, Ellsworth Huntington, and his son, Raphael W. Pumpelly, the studies of the physical basis of the human history, and, after giving them the outline of his hypothesis to prove or disprove, as the facts might decide, he turned to the archeological investigations with enthusiasm. In 1905, when he was entering upon the four years of preparation which intervened between the close of the field-work and the completion of his brief summary of results attained, he said to the writer: "I never could read books on geology; I had to see the facts to become interested, but I can read this by the hour," and he held up "Ripley's Races of Europe."

Very important contributions to our knowledge of the glacial and postglacial conditions which have obtained in central Asia were made by Davis, Huntington, and R. W. Pumpelly as a result of the expeditions.

They are fully set forth in the volume entitled "Explorations in Turkestan," issued by the Carnegie Institution of Washington, in 1905, as Publication Number 26. The archeological results of the second expedition appeared in 1908, under the same general title, as Publication Number 73.

Elected President of the Geological Society of America for 1905, Pumpelly chose for his address a subject drawn from his Asiatic investigations, "Interdependent evolution of oases and civilizations," and presented it at Ottawa in 1906.

Reviewing the field of study in central Asia after his return from the first reconnaissance, in 1904, Pumpelly wrote:

"Judging from our observations and from those of others, especially of the Arabian writers and of the later Russian explorers, it would seem that the country has long been an interior region, dependent for its life mainly on the snows and glaciers of the mountains; that there have been within the present geological period great fluctuations in the amount of water derived from the mountains, as recorded in the high and low shorelines of the seas and in the strata containing living forms left by different expansions of the united waters of the Aral and Caspian, and that man already existed within the region during at least the last great maximum of moisture. . . .

"While we have been surprised at the abundance of the data in natural and artificial records offered by the region, . . . we are impressed with a realization of the intimate relation in which this region stands to the Quaternary and prehistoric history of the whole continent. Physically it forms part of the great interior region extending from the Mediterranean to Manchuria, whose history had been one of progressive desiccation, but in Russian Turkestan the effects of this have been mitigated by the snows of the lofty ranges and the lower altitude of the plains.

"Archeologically this region has, through a long period, been a center of production and commerce, connecting the eastern, western, and southern nations, and its accumulating wealth has made it repeatedly the prey of invading armies. It has been from remote time the field of contact and contest between the Turanian and Aryan stocks; but its problems, both physical and archeological, are parts of the greater problem underlying the study of the development of man and his civilization on the great continent and of the environment conditioning that development."

Allowing Pumpelly to speak further regarding the last scientific work of his long and varied activities, we may quote from the preface to his final report on the work in Turkestan those paragraphs which show his attitude of mind toward his subject, toward his fellow-workers, and in regard to the realization of his dream. He says:

"While each of the investigators was expected to work up his material, there devolved upon me, as initiator and director of the expeditions, the duty of presenting an independent discussion of the results as a whole. I found

myself confronted with the task of translating and editing the contributions of the experts, and of drawing my own conclusions from these and from my own observations. To do this, I surrounded myself with a library of six hundred or more volumes related to our work and problems, besides many borrowed from libraries. Literally living in this problem for nearly four years, my whole time, reading, and thought have been devoted to acquiring such a general survey of the field as would enable me to discuss the subject of our results and of their wider bearing in the light of the present condition of archeological and ethnological knowledge.

"Besides incidental inspection of the museums of Tiflis and Tashkent, numerous visits for study were made to those of Moscow, Saint Petersburg, Berlin, Vienna, Zurich, Schafhausen, Cairo, Athens, London, Naples, and Rome, and to those of Paris, including M. de Morgan's systematically collected finds from Susiana—to me, perhaps the most important of all—and in connection with my chapter on chronology a special journey was made to Egypt to study the rate of growth of Egyptian village mounds in comparison with those of Anau.

"Of the two alternatives, confining the reports, my own included, to a record of observations and finds, or having each contributor go further and, treating his subject from the comparative point of view, draw his conclusions as to the bearing of his results on the general question of Eurasian problems, the latter seemed preferable; for, with the whole chain of observation and thought fresh in mind, it would seem to be the province of the individual investigator to state his inferences, even if only as working hypotheses.

"I confess to having written a chapter on the Aryan problem in the light of an extended study of the whole field and of our own results; but this I have suppressed, because it seemed a premature as well as a hazardous venture for one not already an authority on the subject . . .

"And now, what relation do the results bear to the dream that gave rise to the expeditions? On the physical side, Messrs. Davis, Huntington, and R. W. Pumpelly have traced in high Asia the records of several great glacial expansions during the Glacial Period. The climatic conditions, which during that period so greatly expanded these glaciers and buried Russia under thousands of feet of ice, presumably produced also the inland sea whose shorelines are still visible.

"The evolution of civilization has been traced backward to a time when, before its datings in Babylon and Egypt, man at Anau already lived in cities, cultivated wheat and barley, began the domestication of the useful animals which are our inheritance, and possessed the fundamental industrial arts, including a certain amount of metallurgical knowledge. Evidence has been traced of a progressive desiccation throughout long climatic cycles in whose favorable extremes civilizations flourished, which disappeared in the arid extremes. And that the climatic conditions under which these civilizations vanished gave rise to very early migrations and to a constructive reaction upon the outside world would seem to follow from the early appearance, in Babylonia and Egypt and in the late Stone Age in Europe, of wheat and barley and of breeds of domestic animals which Dr. Duerst identifies with those first established on the Transcaspian oases. . . .

"The reader will see that in tracing back to central Asia the source of the fundamental elements of western civilization, in finding the traces and causes of the inland sea, in discovering evidence of progressive desiccation (and in this the cause of the migrations that revolutionized the world), the dream has to this extent been realized."

This was written at his summer home in Dublin, New Hampshire, in 1908. Might not the old man, who had cherished that dream for forty-four years, have with justice put his statement of its realization more strongly? Might not one who knew his exuberant vitality, his optimism, have expected that he would? But no, his was fundamentally a scientific mind, adhering above all things to the truth as he understood it, and no impulse of self-gratulation could urge him to surpass its limits. In the suppression of his own chapter on the Aryan problem, the ultimate speculation to which he had given years of thought, we see the expression of that supreme loyalty to his ideal of truth which made him truly great.

Dublin, New Hampshire

The last dozen years of Pumpelly's long life were passed at his homes in Newport, Rhode Island, and Dublin, New Hampshire, alternating summer and winter, except when making journeys abroad or in this country for the pleasure and education of his children. Mrs. Pumpelly died in 1915, after forty-six years of married life in a relation more complete in its harmony than falls to the lot of but few. In his loneliness, Pumpelly drew even nearer, if possible, to his children and with them turned to the desert, where "Blessed are the realms of Silence, for in them is the nearness of God." He revisited the scenes of his labors and marvelous escape from Apaches and Mexicans and again plunged into the waterless wastes in search of the Old Yuma Trail, along which he had ridden fifty-four years before. The Ford cars proving less able to cope with the sand than horses had been and the water giving out, the desert almost claimed him permanently as its own; but, with his habitual resourcefulness and the guidance of an Indian as old as he himself, he once more escaped.

Of his life and influence at Dublin, his old classmate and intimate friend, Henry Holt, has written:

"It was most exceptional and it was all unconscious—simply the action and reaction between his character and that of his neighbors. Probably never elsewhere was such a community. He was incomparably the most influential person in the place—ruled it without knowing that he did—unconsciously attracted there all forms of excellence and unconsciously repelled any form

of pettiness. The circle he drew around him blended the highest aristocracy with the simplest democracy. A visitor once described it to a stranger: 'One night you'll go to as lovely a ball as you ever saw, and the next night you'll dine with people you met there who do their own work.' That realization of Utopia those who shared and marveled at it knew was the involuntary work of Pumpelly. He loved all people worth loving and had no other standards; and all people worth loving loved him."

There is nothing to add to this statement of the humanity of this remarkable man. His great soul possessed the magnet of love for his fellow-men, without distinction of creed or race, excluding only the false. His penetrating intellect threw the searchlight beams of his imagination into the unknown realms of knowledge in search of Truth. To her he was ever absolutely loyal, never allowing even a suspicion of egotism to color a statement of fact or to influence his estimate of the validity of an hypothesis. To the Truth he was true. Therefore his contributions to his adopted science, geology, stand unchallenged, monuments to its progress, while he himself takes his place outside the circle of specialists, in the group of great explorers of the physical and intellectual worlds. His thought is being handed down, a living, growing influence, by many who are as unconscious as its author often was of its intense vitality. It lives on because its author invariably put Truth before self.

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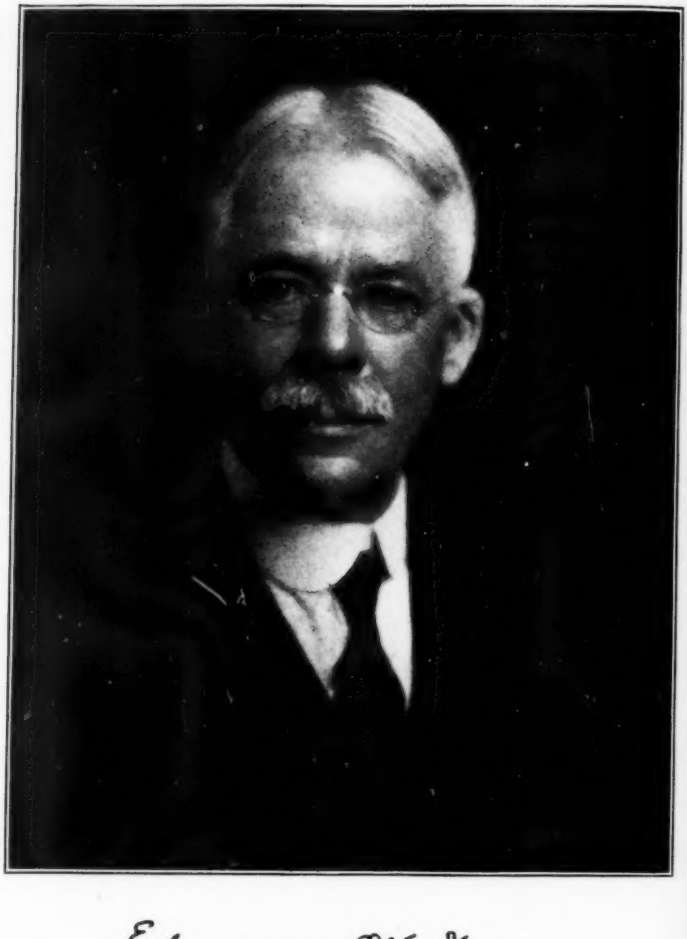

Edmund Otis Hovey.

MEMORIAL OF EDMUND OTIS HOVEY[1]

BY JAMES F. KEMP

The sudden passing of Dr. Edmund Otis Hovey, on September 27, 1924, removed from the Geological Society of America one of its most familiar and influential members. Doctor Hovey was dictating to his secretary, toward the close of the morning hours of work, when taken with a stroke which caused his removal at once to a near-by hospital. While not at first a cause of anxiety, the stroke developed more seriously as the day wore on, and from it he passed away in the early hours of the following day.

Doctor Hovey was identified in a peculiarly intimate way with the Society, almost from its inception. He was an "Original Fellow," by which is meant that he was a working geologist or teacher of geology, one of the members of Section E in the American Association for the Advancement of Science, who signified his desire to join the proposed more specialized Society, and did so by paying the required fee before January 1, 1889. As the Committee of Organization was appointed at the Cleveland meeting of the American Association, August 14, 1888, and the Geological Society was definitely organized December 27 of the same year, with ninety-eight Original Fellows, Doctor Hovey's membership covered almost the full first thirty-six years of its existence. His passing reduced the little band of surviving Original Fellows to twenty-three.

Not only was he himself an Original Fellow, but his father, the Rev. Horace C. Hovey, was also, although an ordained and active clergyman in the Presbyterian communion. The father for many years occupied pulpits in the drainage basins of the Ohio and Mississippi valleys, and was one of our most prolific students of caves. He left on his decease a bibliography of nearly thirty titles relating to these interesting results of underground streams. The record emphasizes the fact that the son passed his early years in a home atmosphere in which geology was an active interest and in which his mind was early directed toward its study.

Edmund Otis Hovey was born in New Haven, Connecticut, September 15, 1862, and was thus, at the time of his death, just past his sixty-second year. He came of a long line of New England ancestry, dating back to Daniel Hovey, who migrated, in 1635, from Waltham, England, to Ipswich, Massachusetts, and became a man of substance and importance. Doctor Hovey's grandfather, after whom he was named, graduated from Dartmouth in 1828, and the Andover Theological Seminary

[1] Manuscript received by the Secretary of the Society January 21, 1925.

in 1830, and became a home missionary in what was then the Middle West. He was one of five ministers who, with five laymen, founded Wabash College, Crawfordsville, Indiana, and in it was professor for forty-four years, teaching especially the natural sciences and being known as one of the pioneer geologists of the State. To him is attributed the discovery of the famous crinoid beds of Crawfordsville. That the father of Edmund Otis had geological interests has been mentioned above.

Doctor Hovey was educated in the public schools of Peoria, Illinois; Kansas City, Missouri, and New Haven, Connecticut, finally preparing for Yale at the Hillhouse High School of the last-named city. He entered in the autumn of 1880 and graduated with the class of 1884. While a student he taught in the evening schools, and on graduating, for two years continued school work at Janesville and Elk River, Minnesota. In the fall of 1886 he returned to Yale for graduate study, geology being his subject of major interest and chemistry and mineralogy the two minor subjects, which in those days every candidate for a higher degree was required to take. In his second year of residence he was assistant in the mineralogical laboratory of the Sheffield Scientific School, and at the end of the year returned to teaching, and was assistant principal of the high school in Waterbury, Connecticut, meantime working on his dissertation. The dissertation completed, he received his degree of Ph. D. in June, 1889. His subject was "Observations on the trap rock ridges of the East Haven-Branford (Connecticut) region," and this, his first important contribution, will be found in the American Journal of Science for November, 1889. The paper is an accurate and careful record of the detailed geology in a district eight or ten miles by four or five, and gave evidence of conscientious fidelity in descriptions and of independence of mind in interpretation.

During his years of graduate study Doctor Hovey came especially under the instruction of the greatly beloved and respected Prof. James D. Dana, second President of this Society. Professor Dana's influence tended in an extraordinary degree to inculcate accuracy and care in statement, combined with consideration and justice toward others. Doctor Hovey's association in the mineralogical laboratory with Prof. Samuel L. Penfield, one of the choice spirits of American science, was also a privilege of exceptional value. The influence of these two teachers, as well as that of others with whom he studied, were deeply impressed upon him.

On completing his doctorate Doctor Hovey turned again to teaching and continued his relationship with the high school in Waterbury, Connecticut, until the summer of 1891. He was at first assistant principal

and later principal. He was given leave of absence during his last year, and went to Europe for study. That his ultimate goal, however, was the career of a geologist is shown by his joining in the movement, in the autumn of 1888, which led to the organization of the Geological Society of America. During the year in Europe, instead of constantly traveling, Doctor and Mrs. Hovey established themselves in places of special interest and kept house for periods of a month. While living in Naples in this way and studying Vesuvius, Doctor Hovey acquired his first experience with an active volcano. In later life, as opportunity offered, he renewed his studies of volcanic phenomena and made them his chief interest. The most important feature of his European stay was work in the laboratory of Professor Rosenbusch at Heidelberg, where he not only learned microscopic petrography, but also made friends with contemporaries abroad, notably J. J. Sederholm, of Finland. his lifelong friend.

On returning to America, in the summer of 1891, Doctor Hovey finally closed his years of school work and sought engagements in geology. He first took charge of the Missouri State Exhibit of Minerals for the approaching Columbian Exposition, in Chicago, in 1893. He brought together a notable display of the lead, zinc, and iron ores, and of the coals, fireclays, glass-sands, and other products of this richly endowed State. From this connection one or two scientific papers ultimately resulted, such as the one on the cherts, cited in the appended bibliography under 1894. When the exposition ended, in the fall of 1893, Doctor Hovey sought other connections, and on January 1, 1894, became assistant curator of geology, under Prof. R. P. Whitfield, in the American Museum of Natural History, New York. In the service of the Museum he remained for the thirty-two years of his subsequent life. In 1901 he became associate curator, and on the decease of Professor Whitfield, in 1910, curator.

Doctor Hovey's first work of prime importance, aside from routine duties, was the joint preparation, with his chief, of a list of the types and figured fossils of the rich collections in the Museum. The completed work of 500 pages was issued in parts during the years 1898 to 1901 and is a most valuable book of reference. During its preparation Doctor Hovey also assembled a catalogue of the Museum's meteorites (1896) and wrote a number of minor contributions.

He was active in the New York Academy of Sciences and a regular attendant at the meetings of the Geological Society of America. He acquired a specialist's knowledge of the effective display of geological objects in a museum, and by the silent influence of these several lines of work developed a habit of mind marked by accurate classification and

orderly arrangement, characteristics which stood out in his subsequent conduct of his secretarial duties in our Society. In later years there seemed to be no act or policy of its Council to which he could not instantly refer by date and page. In 1900 he began editorial work for the Museum, and for the next ten years he had charge of its illustrated magazine, which was at first called "The American Museum Journal," but is now known as "Natural History." From the outset the magazine brought authoritatively prepared, but no less interesting, accounts of work and progress in natural history into the homes of the supporting members of the Museum and of a large circle outside.

In the service of the Museum Doctor Hovey soon began his travels, which became in the end world-wide. The collection and acquisition of new and attractive scientific materials; expeditions for the exploration and study of little-known regions; representation of the Museum at international gatherings of several kinds, but most notably the scientific congresses—all called him to places of extraordinary geological interest and gave him a treasure house of experience and observation as well as an acquaintance with geologists all over the world. In these relations he was sent at once to Martinique when the remarkable explosive outbreak of Mont Pelé startled the scientific world in May and June of 1902. He brought back many observations, illustrative photographs and specimens, upon which a long series of scientific contributions was based. He visited the other islands—Saint Vincent, Guadaloupe, and Dominica—of the Lesser Antilles and studied their heat phenomena, not only on this trip, but on one or two subsequent ones. Besides the scientific papers, one other notable result remains, and that is a large painting of the famous spine of Mont Pelé by the artist Charles R. Knight, based on Doctor Hovey's photographs and now hanging in the meeting room of the New York Academy of Sciences, at the American Museum of Natural History. It was Doctor Hovey's hope to revisit these islands next year and, with a series of observations of recent character, to gather up all his records into a completed whole.

On another trip Doctor Hovey explored a little-known portion of the State of Chihuahua, Mexico, and has left us the record of his observations in papers published in 1907. Excursions to the Black Hills of South Dakota and to the mining regions of Arizona resulted in other short papers or paved the way for the preparation of accurate and impressive museum models. The necessary bringing back of the Crocker Land Expedition of the Museum took Doctor Hovey, in the spring of 1915, to the extreme north of Greenland, where unfavorable ice conditions held him marooned for two years, necessitating a long journey with

sledges to finally escape. But three years after his return from the Arctic, in 1917, we find him amid the volcanoes and semi-tropical conditions of the Hawaiian Islands, where he went as a delegate of the Museum and of other scientific bodies, to the first of the Pan-Pacific scientific congresses. After another three years he proceeded, again as delegate, to the second session of this congress, which was held in Australia. While in Australia he sailed to New Zealand, primarily that he might visit the region of the famous geysers and of other existing volcanic phenomena. In earlier years he attended the International Geological Congresses at Saint Petersburg, 1897; Paris, 1900; Vienna, 1903; Mexico City, 1906; Stockholm, 1910; Canada, 1913; Brussels, 1922, and participated in the attendant excursions. In this way he visited, in 1897, the Caucasus and climbed one of the main peaks of Mount Ararat, the not yet entirely extinct volcano, on the Armenian border. From it he brought back a notable series of fulgurites. In 1903 he traveled in the Austrian Alps; in 1900 in the Pyrenees, and in 1906 covered those portions of Mexico easily accessible by rail and pack train. In the last-named trip the most important excursion was the one to Colima, the still active cone in southwestern Mexico. One sees at once from these world-wide wanderings that the study of volcanic phenomena was the great objective and realize that to this branch of geology Doctor Hovey directed his special interest.

In the first decade of the present century not only editorial but secretarial work was undertaken by Doctor Hovey, with the approval of the Museum authorities and as extra-Museum contributions to the progress of science. In 1907 he was elected Secretary and Editor of the New York Academy of Sciences, and held the positions for nine years, resigning when he set out for the Arctic. Likewise, in 1907, he became Secretary of the Geological Society of America, succeeding Prof. H. L. Fairchild, who had served for seventeen years and desired to retire. Doctor Hovey held the office for sixteen years, retiring at the close of 1922. In appreciation of his long and faithful service, a loving cup was presented to him by the Fellows at the annual banquet of the Ann Arbor meeting (1922). The next year, in Washington, at the annual banquet, the Council expressed to him its appreciation of his long and devoted services in a beautifully engrossed testimonial. The Secretary of the Geological Society of America is the officer who, more than any other, is responsible for the conduct of the Society's affairs. Doctor Hovey's administration was marked by careful and systematic management. His knowledge of the Society's history, politics, and the spirit actuating its successive councils was thorough and accurate. During his incumbency the Society

had to face growing specialization and the subdivision of old interests once brooded under the wings of the present organization. Through all these the parent Society has passed without schism and with continued close relations and cooperation. In no one of the many connections which Doctor Hovey maintained during his life has he left more numerous or more devoted friends than in the Geological Society of America, and in its service he did some of his most important work.

Doctor Hovey entered zealously into many activities of his home city, New York. He was an active member in the Presbyterian Church and a worker in the local group in which he held membership. At the Century Club and in the Explorers' Club he was a familiar figure. At the time of his death he was vice-president of the latter. He was also connected with the American Institute of Mining and Metallurgical Engineers, in the membership of which were many of his friends. In earlier years he was at various times on the staff of the United States Geological Survey, engaged in special services.

Doctor Hovey was a prolific contributor to the literature of geology and about one hundred and fifty titles stand to his credit. Perhaps the most notable contributions related to Mont Pelé, in Martinique, and to La Soufrière, in Saint Vincent. Soon after his return from his first trip to these islands, he read, at the International Geological Congress, in Vienna, an account of his earliest observations. As stated above, it was his plan and ambition to visit again the Lesser Antilles in 1925, and then, with the old notes and new, prepare his complete report. Besides the societies mentioned above, he was a member of the American and National Geographic Societies, a Fellow of the American Association for the Advancement of Science, and was a corresponding member of the Sociedad Científica Antonio Alzate of the City of Mexico.

Doctor Hovey was married September 13, 1888, in New Haven, Connecticut, to Miss Esther Amanda Lancraft, a graduate of Mount Holyoke College and in later years president of its Society of Alumnæ. She died in 1914. On October 23, 1919, Doctor Hovey dispelled the loneliness of his home by his marriage with Miss Dell Geneva Rogers, of Springfield, Massachusetts. Mrs. Hovey, with one daughter, Constance Rogers, born February 3, 1921, survive him.

Doctor Hovey's death, at the age of sixty-two, came while yet many years of active work might reasonably have been expected. Perhaps in no more fitting way can the tribute to him of the Geological Society of America be closed than with the rugged, Anglo-Saxon words of Robert Louis Stevenson, from the close of his essay, "Aes Triplex," in the volume "Virginibus Puerisque":

"It is not only in finished undertakings that we ought to honor useful labor. A spirit goes out of the man who means execution, which outlives the most untimely ending. All who have meant good work with their whole hearts have done good work, although they may die before they have the time to sign it. Every heart that has beat strong and cheerfully has left a hopeful impulse behind it in the world and bettered the tradition of mankind."

NOTE.—Memorials have been published by James F. Kemp, Natural History, volume 24, pages 704-709, December, 1924, with portrait; and by Charles P. Berkey, Science, December 19, 1924, pages 559-560.

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MEMORIAL OF JOHN JAMES STEVENSON [1]

BY I. C. WHITE

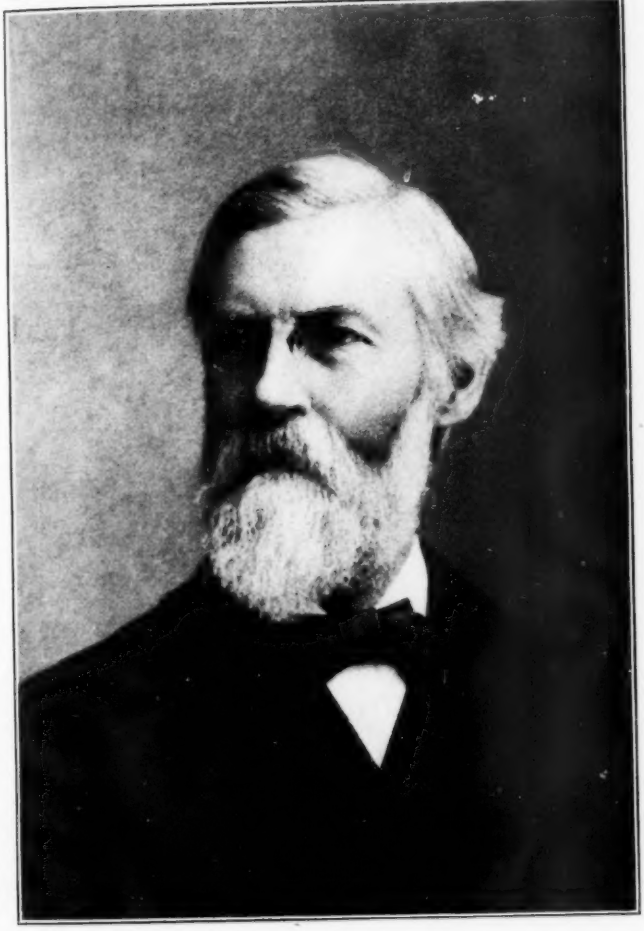
The Nestors of American geology have nearly all answered the final summons. Dr. John James Stevenson, a contemporary and intimate friend of that group of brilliant departed geologists and paleontologists, among whom were numbered Hall, Hitchcock, Cope, Hunt, Sir William Dawson, Lesley, Logan, Marsh, Marcou, Meek, Newberry, Le Conte, Orton, Powell, Pumpelly, Whitney, Whitfield, Alexander Winchell, N. H. Winchell, Worthen, and many others, answered this last roll call on August 10, 1924.

He was one of the thirteen geologists and paleontologists who assembled under the friendly roof of this great university on the 27th day of December, 1888, 36 years ago, to organize this Society, of which we are all so proud. Doctor Stevenson was a member of and secretary of the Committee of Organization of the contemplated new society, appointed by an assemblage of geologists on July 14, 1888, at Cleveland, Ohio. This committee consisted of Alexander Winchell, chairman; J. J. Stevenson, Edward Orton, Charles H. Hitchcock, and J. R. Proctor. As secretary of this committee, most of the actual preliminary work of launching the new society fell to the lot of Doctor Stevenson.

At that date in the history of geologic science there were many personal differences and antagonisms among American geologists, which required the greatest tact and skill as a harmonizer to secure the necessary cooperation and support for the new organization in order that its success might be assured. This difficult task was solved in a masterly way by Secretary Stevenson; so that when the first meeting adjourned at Ithaca, in the afternoon of December 27, 1888, 137 geologists had signified their adhesion to the ranks of the Geological Society of America and 22 others had been elected to membership therein who would become active fellows after January 1, 1889.

At this first meeting of the Society Doctor Stevenson was elected Secretary of the same, and was reelected at the New York meeting, De-

[1] Manuscript received by the Secretary of the Society January 26, 1925.



J. J. Stevenson

cember 26, 1889, for the year 1890. He gave devoted service to the Society in this all-important office until his accomplished successor, Prof. H. L. Fairchild, was elected thereto at the Washington meeting, December 29, 1890. This two years of arduous and efficient labor at the very beginning of the Society's existence, when the work and responsibility connected therewith were greatest and most burdensome, was of inestimable value to the new organization. Hence, while Doctor Stevenson accomplished much brilliant work in many departments of geology, he probably did more for geology in general in the successful launching of this great Society, for which he was so largely responsible, than in any other field of geologic endeavor.

Of the thirteen men who attended the first meeting of this Society at Ithaca, 36 years ago, namely, H. L. Fairchild, James Hall, C. H. Hitchcock, J. F. Kemp, W J McGee, H. B. Nason, J. J. Stevenson, I. C. White, H. S. Williams, J. F. Williams, S. G. Williams, Alexander Winchell, and N. H. Winchell, all are dead except Fairchild, Kemp, and White, Doctor Stevenson being the last to depart, on August 10, 1924, after an attack of pneumonia of two days' duration. He had suffered from arterio-schlerosis and gradual failing eyesight for two years, which compelled him reluctantly to give up all reading and writing of letters except to intimate friends, his last one to me being dated in May, 1924.

Dr. John James Stevenson was born in the city of New York, October 10, 1841, and hence was within two months of rounding out 83 years. He was of Scotch-Irish descent on both sides of the family tree, his father, Rev. Andrew Stevenson, having been born in Ballylaw, Ireland, in 1810, and emigrating to America in 1831, settled in New York City, where he was pastor of one church for 42 years. Doctor Stevenson's mother, whose maiden name was Ann Willson, was born in Bedford Springs, Pennsylvania, in 1811, being a descendant of Zacheus Willson, who came to America in 1711 and settled in Delaware.

Doctor Stevenson was twice married; first, to Mary A. McGowan, of Philadelphia, in April, 1865, to whom three children were born, namely, Anna Warner, who died in 1884; Andrew William, who died in 1869, and Isabella Somerville, living in New Canaan, Connecticut. His first wife having died in 1871, he married Mary C. Ewing, of Uniontown, Pennsylvania, January 1, 1879, who survives him, and to whom two children were born—Margaretta Denny, now Mrs. Albert H. Moore, of Cambridge, Massachusetts, and Archibald Ewing, a lawyer and Government agent, of New York City. One brother survives, namely, Dr. William S. Stevenson, emeritus professor in Occidental College, Los Angeles,

California, now living at Long Beach; also one sister, Mrs. Isabella J. Brock, living at New Canaan, Connecticut.

When only four years old, young Stevenson was sent to Miss Kyle's school, in New York City, for two years, and then to Doctor Brown's school, where he began Greek and Latin, and at the age of eight could read Greek, Latin, and Hebrew, thus giving early evidence of the brilliant mind with which he was endowed. When fully prepared, he entered New York University, and graduated therefrom in the class of 1863. In January, 1864, he was appointed instructor in mathematics and natural science in the Academy of Mexico, New York, and remained there for a few months, resigning to take charge of a small school for boys in September, 1864, at Astoria, New York, where he also edited the American Educational Monthly and worked three hours a day in the Draper Chemical Laboratory, until the autumn of 1867. In June, 1867, he received the degree of Ph. D. from New York University, being the second graduate degree conferred by his Alma Mater.

In the latter part of 1867 he went on a professional trip to the western mining regions to examine and report upon a mine in which some of his friends were interested. During this trip he was exposed to very inclement weather and contracted tuberculosis, from which he was ill for two years, until he came to the West Virginia University as professor of chemistry and natural sciences, in the autumn of 1869, where during the next three years his open-air life in the study of the interesting geology around the vicinity of the university completely cured him of tuberculosis.

In 1871 and 1872 he was assistant to Doctor Newberry on the Geological Survey of Ohio. In January, 1872, he was elected part-time professor of geology at New York University. In 1873 he undertook War Department geologic work under Lieutenant George M. Wheeler, in the Far West, and was appointed geologist of the Colorado party, in charge of Lieutenant W. L. Marshall. In 1875 he was appointed assistant geologist to Prof. J. P. Lesley, State Geologist in charge of the Second Geological Survey of Pennsylvania, and given charge of the detailed geologic work in Greene and Washington counties, with I. C. White as his aid. In 1876 and 1877 he surveyed Fayette and Westmoreland counties for the Second Geological Survey of Pennsylvania and prepared for publication the manuscript of reports thereon, including the report on Greene and Washington counties, which were published as Reports K, KK, and KKK of the volumes of the Second Geological Survey of Pennsylvania. In 1878 he was again actively connected with the Wheeler Surveys in southern Colorado, with the late I. C. Russell as

his aid. In 1879 he did some expert work in southwestern Virginia, as also in 1880, and in 1881 went to New Mexico for the same purpose. During this year (1881) he returned to active work on the Second Geological Survey of Pennsylvania and was assigned to survey Bedford and Fulton counties, which area he completed in 1882, his results being published in volume TT of the Second Geological Survey of Pennsylvania. During this year (1882) he was elected to a full-time professorship in New York University, which position he held until 1909, when he retired as emeritus professor of geology after 38 years of service on the teaching staff of his Alma Mater.

It is a difficult task properly to evaluate the work of one who has covered so skillfully such a large field of human endeavor. First and foremost, Doctor Stevenson was a great teacher, holding the interested attention of his pupils not only by the wonderful breadth of his knowledge of any subject under discussion, but by the charm of his speech and skill in presentation. His students loved and trusted in him, because they knew he was master of his subject and possessed sympathy and the "milk of human kindness" for them. It was this friendly interest and indefinable personal magnetism (which characterize all successful and eminent teachers) that attracted to his class room during his short stay (three years) at West Virginia University not only the writer, but so many other students that he became by far the most popular instructor in the school. It was this subtle influence and attractive personality that turned the writer away from the profession of medicine, which he had seriously contemplated entering, and induced him to center his efforts on geology for his main life's work; so that whatever of success has come to him in this profession is due entirely to the encouragement and inspiration given by his gifted teacher of geology during the impressionable years of student life, and the lasting friendship and sound advice so cheerfully tendered during the subsequent half century.

In the Pan-American Geologist for October, 1924, the editor, Dr. Charles Keyes, has given a review of Doctor Stevenson's life work on pages 161-172, inclusive, in such appreciative and complete detail that it could not be improved on, and hence a large portion of Doctor Keyes' memorial is here reproduced, as follows:

"Doctor Stevenson's contributions to geological science received recognition from fellow-workers in many lands. He was a charter member of the Geological Society of America, and its President in 1899; vice-president of the American Association for the Advancement of Science, 1891; president of the New York Academy of Sciences, 1896-1898; delegate to the International Geological Congress, 1903, and vice-president for the United States, and

member of the American Philosophical Society. He was also a member of many of the foreign learned societies, among them the Geological Societies of Russia, Hungary, Belgium, Vienna, Edinburgh, Liverpool, and Australasia, and the Academies of Science of Moscow, Halle, Dresden, Padua, Palermo, Pisa, and others—thirty-five in all.

"Although he was not what one would call a voluminous writer, Doctor Stevenson's publications were not inconsiderable. His formal memoirs number more than a hundred titles and cover a period of over half a century. His first published contribution to geological science appeared in 1871, and in 1922 his last word on the coal question was printed in this journal, under the title of 'Geological age characteristics of coals,' when, with failing eyesight, he was barely able to supply the data which were in proper sequence put together with loving hands.

"His best-known volumes are the 'Geology of a portion of Colorado,' which forms one of the major reports of the Wheeler Survey (1875); the report on 'Geological examinations in southern Colorado and northern New Mexico,' constituting the supplementary volume III of the Wheeler Survey (1881); 'Geology of Greene and Washington counties, Pennsylvania,' being volume K of the Second Geological Survey of Pennsylvania (1876); 'Geology of Fayette and Westmoreland districts, Pennsylvania,' as volumes KK and KKK of the Pennsylvania Survey (1878); 'Geology of Bedford and Fulton counties, Pennsylvania,' making up volume T2 of the Pennsylvania Survey (1885); 'Carboniferous of the Appalachian Basin,' in volumes XVII and XVIII of the Bulletin of the Geological Society of America (1904); and 'Formation of coal beds' (1913), constituting a volume by itself.

"The geological exploration of southern Colorado was undertaken under such hazardous circumstances that it at once classed Stevenson among the bold pioneers in that geologically unknown country. His first season's operations were in a peculiarly difficult field, where the Rocky Mountains were the loftiest and most inaccessible, where their flanks were clad with dense forests, where the geological age of the formations were wholly undetermined, and where the tectonics had to be deciphered *in toto*. The great marvel of it all is that his conclusions were so accurate that they were not upset even after half a century of subsequent investigation and severest test by many astute observers whose own results served only to confirm the stronger his original contentions.

"The broad features of the regional stratigraphy, which he outlined in no uncertain manner, are quite as unshaken today as when he first determined them. Complete absence or poor representation of the early Paleozoics, the tremendous development of the mid-Carbonic limestones, the Cretacic age of the chief coal measures, and the repeated upraising of the region into mountain chains, albeit peneplanation was undreamed of in his day, are basic generalizations which bring out sharply his consummate skill in grasping geological relationships. 'The Rocky Mountain system is, then, the result of four especially marked upheavals, the first at the close of the Carbonic Period, the second at the close of the Triassic Period, the third at the close of the Cretacic Period, and the fourth during Tertic time. Of these the first and the third are the most general in their effects.' But this early explorer became cognizant of only some of the cycles of orogeny. After his visit there, others

were revealed, until more than 25, all told, were deciphered. Yet his testimony was unshakable, served its immediate purpose, and successfully combatted the then prevailing assumption of only a single upraising of the Rocky Mountains. His conclusions were very opportune and very important in their day.

"Stevenson's work on the Wheeler Survey in northern New Mexico is one of the finest contributions ever made to American stratigraphy. In this investigation, as he himself remarks, particular attention is paid to the stratified rocks. Since these include the coal-bearing formations, the most important, perhaps, on the North American continent, there is to him an added interest. His previous experiences on the Ohio Geological Survey and on the Pennsylvania Survey especially fitted him for the difficult duties devolving upon him in the far-away New Mexico. How well he accomplished what he set out to do there is only very inadequately reflected in the sumptuous volume which he published as one of the quarto series of the United States Geographical Surveys West of the 100th Meridian. In order to fully appreciate how large is the debt which American geology owes this intrepid explorer, one has to go over the same field repeatedly and become thoroughly familiar with all its intricacies.

"Devoting chief attention to the great coal-bearing measures, Professor Stevenson naturally became deeply involved in the Laramie discussion, one of the most prolix controversies which ever disturbed American geology, which at the very time of making his report was waxing its warmest. His conclusion that the New Mexico coals were Cretacic in age was correct in the main for the southern Rocky Mountain region, for the strata with which he came in contact proved in a more recent day to be almost entirely of that age. But that these were contemporaneous with the original Laramie beds of Wyoming is another question. His conclusions are thus stated: 'In view of these facts, (1) that the succession above the Colorado shales to the top of the Laramie is conformable within itself, (2) that no change of importance occurred in the general conditions during the formation of this series, (3) that the Cretacic section from the beginning was a coal-bearing series, (4) that the fauna, wherever of a character to be compared with known standards, is Cretacic, even to the summit of the series, and (5) that the hypothesis that this group or any portion of it is of later date than Cretacic age is unsupported by definite evidence, it seems necessary to regard the Laramie as but the upper part of the Fox Hills group.'

"In the final wind up, however, it was found that the so-called Laramie section of King and the Fort Union section of Hayden were composite successions, Cretacic in age in the lower parts and of Tertic age in the upper portions, the two parts being separated by a notable unconformity. In the Raton field of northeastern New Mexico this latter circumstance entirely escaped Stevenson's notice. It was long years afterwards that its existence there was revealed in a manner that could not be mistaken. So today, with our more complete knowledge the term, Laramie Coal Series is reserved for the Cretacic part of the original section.

"Much might be said concerning Professor Stevenson's latest monographic work, in which the entire field of the coals throughout the world and throughout geological time are passed in review. This summary on the 'Formation of coal beds' treats basic peculiarities of the accumulation of the

coal deposits. Other phases are included in a masterly essay entitled the 'Interrelations of the fossil fuels.' Closely related problems have to do with the ascertainment of the relations of the fossil fuels, other than petroleum, in their physical and chemical resemblances and differences. The central thought expressed is that since the extent of chemical change of rocks increases, as a rule, proportionally to the antiquity of the deposits, the tenor of the fossil fuels is advantageously considered in the order of their occurrence in geological time.

"Although during a great part of his life Doctor Stevenson was a hard-working—aye, overworked—college professor in a rapidly expanding, much undermanned, and rapidly changing city institution, where one's time is literally gulped down in huge chunks, he found ample relax in scientific investigation, which often took on the form of pure delight at extending his knowledge in little known or perfectly unknown fields. Many of his important observations and results never saw light of day in finished form in the regular publication channels and knowledge of their existence only trickled through to the outside world from the lecture hall.

"Stevenson was really a man of many parts. He was a naturalist of the old school, intensely interested in all Nature about him—her varied moods, her innumerable mysteries. The plants, the beasts of the field, the birds of the air, the fishes of the sea, came in for due attention, along with the rocks and the minerals. Those who were privileged to know him intimately or as a friend not only respected and admired the compass of his learning and his virile personality, but felt for him an affectionate regard.

"Although enjoying health and happiness to the full for a full decade beyond utmost limit set by Psalmist, and although eye was at last dim, the mind was bright to the very last moment of life. Up to the very day of dissolution, he took lively interest in all affairs of the day. His last book on the 'Formation of coal beds' was published in unfinished form. It was only half completed. Failing eyesight due to gathering cataracts forced secession from all reading. His grim determination to go on and his hopeful spirit yet to continue is characteristically shown in his last letter to me, written a year before his demise, when it was a real effort for him to communicate by pen:

"'DEAR DR. KEYES:

"'You have done much work on coal and are perfectly competent to discuss any book on that subject. So if you should prepare a note on my last volume, print it as your own. It would not be right to print it under my name. I can not prepare the notice myself, as is well known and understood by a number of the eastern geologists.

"'Notwithstanding the fact that I am one of the "has beens," I trust you will be successful in your new venture, for which there is ample room now in geological circles. I regret much that it will be of no use to me, for my vision is becoming so poor, owing to cataracts, that eye-strain trouble follows all reading, and the oculist says that an operation would not be advisable at present. But within a few months I may be ready for the surgeon's help. If he succeeds, reading may be as easy as of old.

"'I trust that your magazine is succeeding; it deserves success, and you are to be congratulated.'

"'Sincerely yours, J. J. STEVENSON.'

"Professor Stevenson had a keen sense of quiet humor and great personal charm, which endeared him to a host of friends. He was one of the most kindly, modest, and upright of men, courteous with that courtesy which we now call old-fashioned. Busiest of men, he was always at the disposal of his friends. To visit him on an evening in his own cozy home, in his marvel of a 'den,' when he was settling down to the work that he loved so well and that he lived so long for, was a lesson in largeness of heart and a stimulus to research that did not speedily pass away. His energy was as striking as his versatility, and he lived a full life, happy in his family and in his innumerable friends.

"With Stevenson's passing it seems as if the last links with the heroic age of our science were severed."

In this same article Prof. H. L. Fairchild, of Rochester University, and a lifelong friend of Doctor Stevenson, speaks of his personality as follows:

"Stevenson had a singularly pleasing personality, and was a most interesting raconteur of incidents and personalities connected with his geological associations. If he has left, as is hoped, an autobiography, it should be very entertaining to all those who knew him and the geologists of former years.

"Like his contemporaries, he was largely self-taught; but he became an authority, probably the leading American authority of his time, on coal and carboniferous stratigraphy. His interest in geology did not range widely. In later years he was engaged on an ambitious work on coal which, unfortunately, he was not able to complete.

"He was interested in education and sociology, and some of his articles on these subjects were very keen, humorous, and effective. He enjoyed a good-natured fight, and found a field for his cheerful combativeness in the Republican organization of New York City and in the councils of the Presbyterian Church.

"To me the passing of Doctor Stevenson is a keen personal loss. Going to New York in 1877, he was one of my first acquaintances and was always a loyal and helpful friend."

In this article personal tributes and incidents in the life of Doctor Stevenson are also given by Dr. John H. Finley, President of the University of the State of New York; Dr. James F. Kemp, of Columbia University, and by I. C. White, who relates the details of Doctor Stevenson's work and life at West Virginia University, all very interesting in themselves, but too long to quote in this connection.

Another notable contribution to the detailed stratigraphy of the Coal Measures first announced by Doctor Stevenson is the fact that each individual coal bed of the Pennsylvanian has "earmarks" or peculiarities of its own, from which the careful geologist can recognize any particular coal bed over a wide area. These are the quality of the coal itself, the arrangement and character of its parting slates, as also the quality of the roof and bottom.

His geologic work in the study of the detailed structure of the Pittsburgh coal bed while located in the vicinity of its greatest development at Morgantown, West Virginia, and his later study and description of the same bed in his Reports K, KK, and KKK of the Second Geological Survey of Pennsylvania in Greene, Washington, Fayette and Westmoreland counties, as also his study of the same coal bed (number 8) for the Ohio Geological Survey, mark the beginning of detailed coal bed stratigraphy in American geology.

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MEMORIAL OF THOMAS L. WATSON [1]

BY H. RIES

Thomas Leonard Watson, head of the Department of Geology in the University of Virginia, and State Geologist of Virginia, died on November 10, 1924.

Doctor Watson was born at Chatham, Virginia, September 5, 1871, and came of an old Virginia family, several of whose members were prominent as educators or in the legal profession. He received his college education at the Virginia Agricultural and Mechanical College (now Virginia Polytechnic Institute), graduating from there with the B. Sc. degree in 1890 and with the expectation of taking up chemistry as a profession. After a year of graduate work at the University of Virginia, he returned to his Alma Mater, where he held an instructorship from 1892-1895, carrying on further graduate work at the same time to receive his M. Sc. degree in 1893. During this period, from 1890-1895, he also worked as assistant chemist at the Virginia Experiment Station.

In 1895 he went to Cornell University, where he remained until 1897, taking his Ph. D. degree there. While at Cornell he took part in the Cornell Expedition to Greenland, in the summer of 1896, and published the results of some of his observations made on that trip.

Leaving Cornell, he was engaged for a year in the United States National Museum as private research worker on rock decay, a subject in which he retained a deep interest during his lifetime and regarding which he published a number of papers. Living, as he did, in the South, where weathering is often deep and varied, he found a fertile field for this line of investigation.

The next three years, from 1898-1901, Watson spent as Assistant State Geologist of Georgia, during which period he carried on studies of the granites, bauxites, and ochers of that State, which were really the first ones of a long series of reports and papers from his pen dealing with the economic geology of the Southern States—a field in which he became an authority and regarding which he had hoped in later years to prepare for private publication a comprehensive work.

He was temporarily drawn away from the South, however, by accepting the chair of geology at Denison University, although he still spent his summers at field-work in the South, partly for the United States Geological Survey and partly for the North Carolina Survey. These field seasons, as well as several others that followed, resulted in the pub-

[1] Manuscript received by the Secretary of the Society February 2, 1925.

Thomas L. Walker.

lication of work, in part jointly with others, on the granites of the Southern States and several interesting papers of a petrographic character.

When the call came in 1904 to return to his native State as professor of geology at his Alma Mater, now the Virginia Polytechnic Institute, he promptly accepted it, for he saw a great chance to develop what became his life work, namely, a study of the geology and mineral resources of Virginia. Indeed, it was his strong interest in this which led him to abandon chemistry for geology.

It was while at Blacksburg that in 1904 arrangements were made by the Virginia Board of Agriculture and Immigration and the Board of Visitors of the Virginia Polytechnic Institute for a geological survey of the mineral resources of Virginia, and Doctor Watson was appointed geologist in charge of the survey. As a result of this commission, Watson personally prepared a bulletin on the lead and zinc deposits of Virginia, and also had two others made, one on the clay deposits of the Virginia Coastal Plain by the writer and one on the hydrography of Virginia by N. C. Grover and R. H. Bolster.

In 1907 Doctor Watson was called to the University of Virginia to take the chair of economic geology and made head of the department in 1910. The change to Charlottesville pleased him greatly, for he felt that it would give him the desired opportunity to carry on more effectively the geological work in Virginia, in which his interest was deeply rooted. A still further step in this direction was the revival, by legislative enactment in 1909, of the Virginia Geological Survey, with Doctor Watson as State Geologist and director. The only official geological survey of Virginia up to that time was the work done by Prof. W. B. Rogers between 1835 and 1842 and the private survey made by Watson while at the Virginia Polytechnic Institute. From the date of his appointment as State Geologist until his death, Watson applied himself most energetically to the development of the Virginia Geological Survey—a task for which he was especially fitted, for he had spent a large part of his life in the State and was peculiarly familiar with it and the work to be done. In the fifteen years that he was State Geologist there appeared a number of reports, many of them of detailed character, dealing with the different phases of geologic work as applied to Virginia. Aside from their scientific value, they represent a high order of editorial merit.

Although many of the bulletins were by others than himself, Watson spent most of the summer in the field with the different workers, taking part in their work and always being thoroughly familiar with it.

One of his bulletins which has attracted considerable attention is that on the geology of the titanium and apatite deposits of Virginia, which

deals with one of the most interesting igneous complexes in the eastern United States. He had also partially completed reports on two other especially interesting areas, those of the emery deposits in Pittsylvania County and the pyrite deposits of the Piedmont area, both of which presented important problems in economic geology and petrography.

One of his largest contributions was a volume on the Mineral Resources of Virginia, issued in connection with the Jamestown Exposition. This was not a small handbook, written in popular style, as such publications are apt to be, but a thorough discussion, covering 618 pages and dealing with the geology and mineral resources of the State, in which he set forth what was known regarding Virginia.

Doctor Watson was coauthor with the writer of two textbooks on engineering geology. Although this work was of a somewhat arduous nature, the writer will always think of it with pleasure, for he assumes that it is rare to fine a coauthor with whom one can work for a long period without some strong feeling of disagreement. Perhaps this was due to the fact that we agreed beforehand to accept each other's criticisms in the proper spirit, no matter how severe they might be.

In addition to his strenuous duties as State Geologist, Doctor Watson also devoted much time to his work of teaching, and here he gave the same attention to detail as in his field-work. As a teacher he was eminently successful; for, besides having a background of practical experience in geology, he carried on his work with an earnestness and enthusiasm which were bound to yield good results. This is testified to not only by the expression of affectionate regard uttered by all his former pupils, but also by the creditable work which they have done since leaving the university.

Watson was a man of tremendous energy, a tireless worker, and he therefore set a splendid example to those associated with him. He also possessed other qualities which are important requisites in the make-up of a good geologist and research worker. He had keen powers of observation, his reasoning was always careful, and his descriptions accurate. His scientific ideals were high and he lived up to them.

Another thing that added to his efficiency, as expressed by one of his fellow-geologists, was the expedition with which he turned out work and his fine memory for geologic occurrences and facts.

His particular interest was in economic geology, mineralogy, and petrography; but this did not detract in anyway from his broad interest in all the other branches of geology, and that he had a familiarity with them is shown by the quality of his papers on geologic topics outside of the territory of his specialties.

During recent years Doctor Watson had devoted considerable attention to the work of a revised nomenclature and classification of minerals, which was being carried on by a committee of the Mineralogical Society of America, of which he was chairman. Some of the work of this committee has already been reported in the American Mineralogist.

The writer had been associated with Doctor Watson for many years, as a personal friend and scientific associate, and while his regard for him as a scientist was high, his personal traits of character appealed to him no less strongly. He never was an advertiser, but, on the contrary, was exceedingly modest. He was uniformly courteous, and, as one friend said, "He inherited all the qualities of a gentleman and in every respect lived up to his inheritance." Another outstanding characteristic was his loyalty, not only to his profession, but also to his friends. He was a man possessing the highest sense of honor, and never during the entire time he served as State Geologist was the slightest hint of commercialism attached to his name.

During the last few years of his life Doctor Watson suffered much from ill health, but few of his acquaintances realized it, and while under these conditions many another man would have retired for recuperation, his stern sense of duty and loyalty to his work impelled him to go on.

Doctor Watson was a fellow of the Geological Society of America, the Mineralogical Society of America, and American Association for the Advancement of Science; he was a member of the Society of Economic Geologists, American Institute of Mining and Metallurgical Engineers, Geological Society of Washington, Washington Academy of Sciences, and Seismological Society of America.

He had served as a councilor of the Mineralogical Society and the Geological Society of America, as a member of a subcommittee of the National Research Council, the Committee of 100 on Scientific Research, and member of the executive committee of the National Conservation Congress. He was also a member of Sigma Xi and Phi Beta Kappa.

He was married in 1899 to Miss Adelaide Stephenson, and is survived by his wife and six children, to all of whom our sympathy is extended.

Although Doctor Watson's career is finished, the record of his scientific work will remain as a monument to the man who had so loyally served the science he loved and also his native State.

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50. Annual report on the mineral production of Virginia during the calendar year 1908. Virginia Geological Survey, Bulletin number I-A, 1909, 141 pages, 1 plate (map), 25 figures.
51. The manganese ore deposits of Georgia. Economic Geology, volume 4, 1909, pages 46-55.
52. Petrology of the South Carolina granites. Journal of Geology, volume 17, 1909, pages 730-751, 5 figures.
53. A résumé of the work of the Virginia Geological Survey for the year 1909. Alumni Bulletin, University of Virginia, volume II, third series, number 3, 1909, pages 308-312.
54. Granites of the southeastern Atlantic States. United States Geological Survey, Bulletin 426, 1910, 282 pages, 27 plates, 20 figures.
55. Intermediate (quartz monzonitic) character of the central and southern Appalachian granites, with a comparative study of the granites of New England and the western United States. Bulletin of the University of

Virginia Philosophical Society, Scientific Section, volume 1, number 1, 1910, pages 1-40, 3 figures.

56. Discovery of fossils in the Quantico slate belt, and the association of volcanic-sedimentary beds with the slates of the Virginia crystalline region. (Thomas L. Watson and S. L. Powell.) Abstract, Bulletin of the Geological Society of America, volume 21, 1910, page 782.
57. The commercial importance of the Virginia pyrite deposits. Appalachian Industrial Record, volume 1, number 3, pages 8-10, February, 1910.
58. Review of "Annual report on the mineral production of Virginia during the calendar year 1908." Virginia Geological Survey, Bulletin number I-A, 1909, 141 pages, 1 map, 26 figures; "The cement resources of Virginia west of the Blue Ridge, Virginia Geological Survey, Bulletin number II-A, 1909, 309 pages, 30 plates, 30 figures; Alumni Bulletin, University of Virginia, volume III, third series, number 1, 1910, pages 80-84.
59. The Virginia rutile deposits. (Thomas L. Watson and S. Taber.) United States Geological Survey, Bulletin 430-D, 1909, pages 52-65; Bulletin 430, 1910, pages 200-213, 2 figures.
60. Nelsonite, a new rock type; its occurrence, association, and composition. Abstract, Bulletin of the Geological Society of America, volume 21, 1910, page 787.
61. The commercial importance of the Virginia pyrite deposits. Appalachian Industrial Record, volume 1, number 3, February, 1910, pages 8-10.
62. Mineral production of Virginia in 1910. Mining and Engineering World, November 11, 1911, page 996.
63. Administrative report of the State Geologist for the biennial period 1908-1909. Virginia Geological Survey, 1910, 31 pages, 1 figure.
64. The commercial importance of the Virginia pyrite deposits. Appalachian Mines and Industrial Record, volume 1, number 3, 1910 (old number, volume 5, number 2), pages 8-10, 1 figure (map).
65. A geological map of Virginia; scale, 1:500,000. Virginia Geological Survey, 1911.
66. Biennial report on the mineral production of Virginia during the calendar years 1909-1910. Virginia Geological Survey, Bulletin number VI, 1911, 123 pages.
67. Underground temperatures. Science, new series, volume 33, 1911, pages 828-831.
68. West Elizabeth, Pennsylvania, deep well. Science, new series, volume 34, 1911, pages 125-126.
69. Completion of the new geological map of Virginia. Mining and Engineering World, volume 35, 1911, pages 6-8; Alumni Bulletin, University of Virginia, volume IV, third series, number 5, 1911, pages 582-587.
70. Fossil evidence of the age of the Virginia piedmont slates. (Thomas L. Watson and S. L. Powell.) American Journal of Science, fourth series, volume 30, 1911, pages 33-44, 8 figures.
71. Association of rutile and cyanite from a new locality. (Thomas L. Watson and Joel H. Watkins.) American Journal of Science, fourth series, volume 32, 1911, pages 195-201, 3 figures.
72. Administrative report of the State Geologist for the biennial period 1910-1911. Virginia Geological Survey, 1912, 25 pages.

73. Economic products of the Virginia Coastal Plain. Virginia Geological Survey, Bulletin number IV, 1912, pages 223-263, 3 plates.
74. An association of native gold with sillimanite. American Journal of Science, fourth series, volume 33, 1912, pages 241-244, 2 figures.
75. Vanadium and chromium and rutile and the possible effect of vanadium on color. Journal of the Washington Academy of Sciences, volume 2, number 18, 1912, pages 431-434.
76. Kragerite, a rutile-bearing rock from Krageroe, Norway. American Journal of Science, fourth series, volume 34, 1912, pages 509-514.
77. Zirconiferous sandstone near Ashland, Virginia, with a summary of the properties, occurrence, and uses of zircon in general. (Thomas L. Watson and Frank L. Hess.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 11, 1912, pages 267-292, 2 plates, 2 figures (including map).
78. Commercial importance of Wise County minerals. Southern Community Advertiser, The Wise County, Virginia, number, November, 1912, pages 11-12.
79. A contribution to the geology and mineralogy of Graves Mountain, Georgia. (Thomas L. Watson and J. Wilbur Watson.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 7, 1912, pages 200-221, 2 figures.
80. Biennial report on the mineral production of Virginia during the calendar years 1911 and 1912. Virginia Geological Survey, Bulletin number VIII, 1913, 76 pages, 2 plates, 8 figures.
81. T. L. Watson and J. S. Grasty: The barte deposits of Tennessee. The Tradesman, May 1, 1913, pages 34 to 38.
82. T. L. Watson and J. S. Grasty: The geology and barite deposits of the Cartersville, Georgia, district. The Tradesman, May 22, 1913, pages 35 to 37.
83. The mineral resources of Virginia. Mining and Scientific Press, volume 106, pages 898-900, 947-949, 5 figures; volume 107, 1913, pages 14-15.
84. A meteoric iron from Paulding County, Georgia. American Journal of Science, fourth series, volume 36, 1913, pages 165-168, 2 figures.
85. Petrology of a series of igneous dikes in central western Virginia. (Thomas L. Watson and Justus H. Cline.) Bulletin of the Geological Society of America, volume 24, 1913, pages 301-334, 3 plates, 5 figures.
86. Petrology of a series of nepheline syenite, camptonite, monchiquite, and diabase dikes in middle Shenandoah Valley, Virginia. (Thomas L. Watson and Justus H. Cline.) Abstract, Bulletin of the Geological Society of America, volume 24, pages 682-683.
87. Normal faulting in the Cambrian of northern piedmont, Virginia. (Thomas L. Watson and Justus H. Cline.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 16, 1913, pages 341-347, 3 figures (including map).
88. Drainage changes in the Shenandoah Valley region of Virginia. (Thomas L. Watson and Justus H. Cline.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 17, 1913, pages 349-363, 7 plates (including map), 5 figures.

89. Zirconiferous sandstone near Ashland, Virginia. (Thomas L. Watson and Frank L. Hess.) United States Geological Survey, Bulletin 530-P, 1912, 9 pages; Bulletin 530, 1913, pages 165-171; Virginia Geological Survey, Bulletin number VIII, 1913, pages 40-50, 2 plates, 2 figures.
90. Geology of the titanium and apatite deposits of Virginia. (Thomas L. Watson and S. Taber. Virginia Geological Survey, Bulletin number III-A, 1913, 308 pages, 37 plates (plate 1, map in pocket), 22 figures (including maps).
91. Magmatic names proposed in the quantitative system of classification for some new rock types in Virginia. (Thomas L. Watson and S. Taber.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 14, 1913, pages 331-333.
92. Igneous complex of high titanium-phosphorus-bearing rocks of Amherst-Nelson counties, Virginia. (Thomas L. Watson and S. Taber.) Abstract, Bulletin of the Geological Society of America, volume 24, 1913, page 682.
93. Mineral production of Virginia in 1912. Mining and Scientific Press, December 6, 1913, page 898.
94. Administrative report of the State Geologist for the biennial period 1912-1913. Virginia Geological Survey, 1914, 49 pages.
95. The rutile deposits of the eastern United States. United States Geological Survey, Bulletin 580, 1914, pages 385-412, 5 figures (maps).
96. Memorial of William M. Fontaine. Bulletin of the Geological Society of America, volume 25, 1914, pages 6-12.
97. Engineering Geology. (H. Ries and Thomas L. Watson.) Volume XXVI, 672 pages, 104 plates, 225 figures. New York, John Wiley and Sons, 1914.
98. The piedmont limestones of the southeast Atlantic States. (Thomas L. Watson and J. S. Grasty.) Abstract, Science, new series, volume 39, March 13, 1914, page 400.
99. The cement materials and industry of the Southern States. (Thomas L. Watson and J. S. Grasty.) Abstract, Science, new series, volume 39, March 13, 1914, page 400.
100. Examples of intercision type of stream piracy in western Virginia. (Thomas L. Watson, Justus H. Cline, and T. K. Harnsberger.) Bulletin of the University of Virginia Philosophical Society, Scientific Section, volume 1, number 20, July, 1914, pages 437-442, 4 figures.
101. Mineral production of Virginia, 1913. Mining and Scientific Press, August 29, 1914, page 334.
102. Extrusive basalt of Cambrian age in the Blue Ridge of Virginia. (Thomas L. Watson and Justus H. Cline.) American Journal of Science, fourth series, volume 39, 1915, pages 665-669, 1 figure.
103. Hypersthene syenite (akerite) of the middle and northern Blue Ridge region, Virginia. (Thomas L. Watson and Justus H. Cline.) Abstract, Bulletin of the Geological Society of America, volume 36, 1915, pages 82-83.
104. Barite of the Appalachian States. (Thomas L. Watson and J. S. Grasty.) American Institute of Mining Engineers, Bulletin number 98, 1915,

pages 345-390, 22 figures (including maps). Transactions, volume 51, 1916, pages 514-559, 22 figures (including maps).

105. Engineering Geology. (H. Ries and Thomas L. Watson.) Second edition, enlarged, volume XXVII, 722 pages, 104 plates, 249 figures. New York, John Wiley and Sons, 1915.

106. Administrative report of the State Geologist for the biennial period 1914-1915. Virginia Geological Survey, 1916, 45 pages.

107. Zircon-bearing pegmatites in Virginia. American Institute of Mining Engineers, Bulletin number 115, 1916, pages 1237-1243, 1 figure. Transactions, volume 55, 1917, pages 936-942, 1 figure.

108. Hypersthene syenite and related rocks of the Blue Ridge region, Virginia. (Thomas L. Watson and Justus H. Cline.) Bulletin of the Geological Society of America, volume 27, 1916, pages 193-234, 1 figure (map).

109. A geological map of Virginia (reprint of map of 1911, with slight revision); scale, 1:500,000. Virginia Geological Survey, 1916.

110. Virginia [physiography]. The New International Encyclopædia, New York, 1916.

111. Weathering of allanite. Bulletin of the Geological Society of America, volume 28, 1917, pages 463-500. Abstract, 1917, page 152.

112. Titanium; its occurrence and commercial uses. Mineral Foote-Notes, volume 1, number 12, 1917, pages 5-15.

113. The color of amethyst, rose, and blue varieties of quartz. (Thomas L. Watson and R. E. Beard.) Proceedings of the United States National Museum, volume 53, 1917, pages 553-563.

114. Administrative report of the State Geologist for the biennial period 1916-1917, by Thomas L. Watson, 1918, 36 pages.

115. The relations of sphalerite to other sulphides in ores (discussion). American Institute of Mining Engineers, Bulletin number 136, 1918, pages 843-845.

116. Manganese, its occurrence and commercial uses. Mineral Foote-notes, volume 2, number 6, 1918, pages 3-12.

117. The color change in vivianite and its effect on the optical properties. American Mineralogist, volume 3, 1918, pages 159-161.

118. Pyrolusite from Virginia. Journal of the Washington Academy of Sciences, volume 8, number 16, 1918, pages 550-560, 1 figure.

119. The Virginia earthquake of April 9, 1918. Bulletin of the Seismological Society of America, volume 8, number 4, 1918, pages 105-116, map.

120. Mineral resources of Virginia in the chemical industries. Metalurgical and Chemical Engineer, volume 18, 1918, pages 456-457.

121. Sulphur, pyrites, and sulphuric acid in 1917, by Philip S. Smith. Virginia, by Thomas L. Watson, pages 51-55. Mineral Resources of the United States, United States Geological Survey, part II, 1918, pages 19-62.

122. Vivianite from the land pebble phosphate deposits of Florida. (Thomas L. Watson and S. D. Gooch.) Journal of the Washington Academy of Sciences, volume 8, number 4, 1918, pages 82-88.

123. Titanium-bearing corundum-spinellite (rock emery); a preliminary statement of its occurrence and composition in Virginia. (Thomas L. Wat-

son and George Steiger.) Journal of the Washington Academy of Sciences, volume 8, number 21, 1918, pages 665-676.

124. Glass-sand resources of Virginia. Journal of the American Ceramic Society, volume 2, number 10, 1919, pages 794-803.

125. Earthquake in Warren and Rappahannock counties, Virginia. Bulletin of the Seismological Society of America, volume IX, number 4, 1919, pages 128-134, figures.

126. Alabama meeting of the Association of American State Geologists. Science, January 2, 1920, page 191.

127. State geological surveys. The American Year Book for 1919, New York, pages 300-303, 1920.

128. Note on the composition of allanite. American Mineralogist, volume 5, number 1, 1920, pages 6-7.

129. Administrative report of the State Geologist for the biennial period 1918-1919. Virginia Geological Survey, 1920, 31 pages, 1 plate (map).

130. Bearing of experimental chemical data on the formation of Smithsonite. Bulletin of the Geological Society of America, volume 31, 1920, page 161.

131. Elements of Engineering Geology. (H. Ries and Thomas L. Watson), 252 pages, figures. New York, John Wiley and Sons, 1921.

132. Petrography of a lamprophyre dike cutting a pyrite body in Boyd-Smith mine in Louisa County, Virginia. Reprinted from the Journal of the Washington Academy of Sciences, volume 11, number 14, August 19, 1921, pages 341-345.

133. Lazulite of Graves Mountain, Georgia, with notes on other occurrences in the United States. Journal of the Washington Academy of Sciences, volume 11, number 16, October 4, 1921, pages 386-391.

134. A contribution to the geology of the Virginia emery deposits. Economic Geology, volume 18, 1923, pages 53-76, with figures 17-21, and plate iii. (Presented to the Society of Economic Geologists, Amherst, Massachusetts, meeting, December, 1921.)

135. Rutile-ilmenite intergrowths. The American Mineralogist, November, 1922, volume 7, number 11, pages 185-188.

136. Geology of a vein occurrence of rutile-ilmenite in a new locality. Journal of the Washington Academy of Sciences, volume 12, number 20, December 4, 1922, pages 447-454.

137. Native copper deposits of the South Atlantic States compared with those of Michigan. Economic Geology, volume 18, 1923, pages 732-752, with map, figure 105. (Presented to the Society of Economic Geologists, Ann Arbor, Michigan, meeting, December, 1922.)

138. The Sharps meteorite, Richmond County, Virginia. Proceedings of the United States National Museum, volume 64, 1923, article 2, pages 1-4, with plates 1-2.

139. Thermal springs of the southeast Atlantic States. The Journal of Geology, volume XXXII, number 5, July-August, 1924, pages 373-384, with figures 1-2.

140. Hoegbomite from Virginia. Presented to the Mineralogical Society of America at the Washington, D. C., meeting, December, 1923. American Mineralogist, February, 1925.

141. Report of the Committee on Nomenclature and Classification of the Mineralogical Society of America. Presented by the chairman (Thomas L. Watson) for the committee to the Mineralogical Society of America at the Washington, D. C., meeting, December, 1923. (In press, for publication in the American Mineralogist.)

142. Engineering Geology. (H. Ries and Thomas L. Watson.) Third edition, John Wiley and Sons, New York, 1925.

MEMORIAL TRIBUTE TO SIR ARCHIBALD GEIKIE [1]

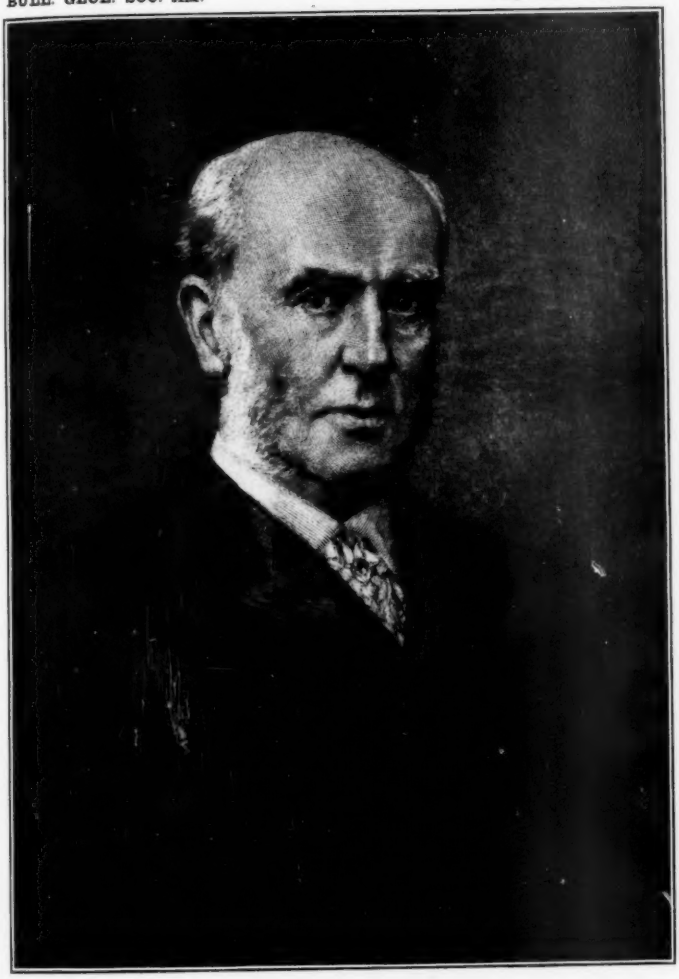
BY JOHN M. CLARKE

Sir Archibald Geikie, whose death occurred in November last, was and had been, since the death of Suess, the great outstanding figure in geological science in the world. He had covered the whole scale of achievement, honor, and preferment in Science, was honored in every country by the highest tributes of distinction, and in his own no geologist ever attained the degree of public recognition that fell to him. Professor in the University of Edinburgh, Director of the Geological Survey of Scotland, Director-General of the Geological Survey of Great Britain, twice President of the Geological Society of London, one of these terms being his special election for the extraordinary Centenary Celebration of 1907; Secretary and afterwards President of the Royal Society; recipient of the Order of Merit; Knighted by his sovereign, and in his last days holding to the position and dignity of Foreign Secretary of the Geological Society—this is an array of distinguished service and recognition that seldom has fallen to the lot of a scientific man.

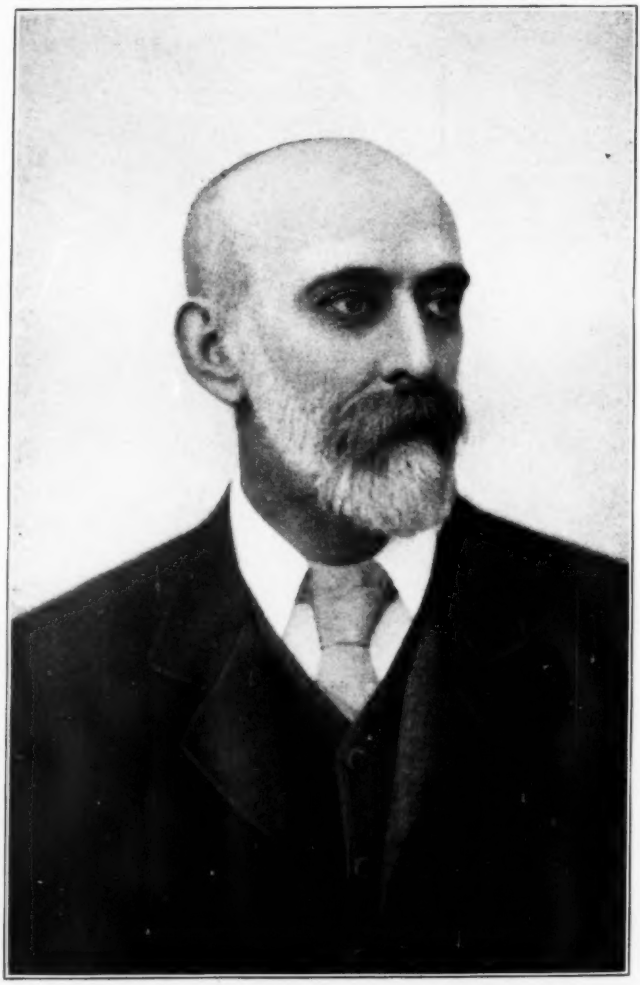
One looks over the titles of Geikie's works, his official reports, his textbooks, his popular writings on geology, scenery, and personal reminiscence with amazement at their number and grasp, but among the virtues of his home training, chiefest was that of diligence. With perfect physical equipment, he never tired, either in the field or out, and with perfect patience and indefatigable industry he abstracted every article in his science that came to his hand, and with perfect orderliness filed them for use. It is only thus we account for his encyclopedic Textbook of Geology, which would seem to be the work of an army of collaborators rather than that of one man. Scotch, he was canny of his scientific property and entered into no partnerships.

Geikie, writing his autobiography at 87 and not living, we think, to read both the applause and the strictures which it has called forth, recounted there and elsewhere the episodes of his acquaintance with Hugh Miller, from whose writings he himself won the translucent literary style

[1] Manuscript received by the Secretary of the Society December 29, 1924.



SIR ARCHIBALD GEIKIE



Yours faithfully
J. J. H. Teall

which has given such grace to his more popular books. But, in spite of these contacts and influences, Geikie's literary excellence, not equaled by any geologist of his generation, did not rise to the level of Hugh Miller's master hand. Sir Roderick Murchison was his chief and his deity. He was to succeed him as Director-General, and for this counselor of his Scottish days and his adviser in British days he named his only son.

For this Society, perhaps Geikie's closest touch was the event of his coming to America to deliver the first course of lectures, under the George H. Williams Foundation, at the Johns Hopkins University, on the general title of *The Founders of Geology*. Some of us here participated in the delightful program of events which surrounded those pleasant days and which was so effectively arranged by our lamented member, William Bullock Clark. The occasion brought Sir Archibald into contact with and enabled him to receive the acclaim of a large number of our most eminent men in geology. It was my pleasure in later years to travel with Sir Archibald through the highlands of Scotland, and to share his endless repertory of stories of every hue. He was always sane, sound, self-possessed, and self-centered, for he could not fail to be conscious of the geological influences that revolved about him. Our correspondence was never long interrupted, and my last letter from him came only a week or two before his death, in which he reproached me for staying too long on my job and earnestly advised me to step out and look back over the work I had done—advice which I have declined to take, as tomorrow interests me much more than yesterday.

There was nothing humanly to be added to Geikie's life. It was full, rounded, complete, and honored of his fellows. We have to be thankful that there have been such men.

MEMORIAL TRIBUTE TO SIR JETHRO J. H. TEALL [1]

BY WHITMAN CROSS

In the death of Sir Jethro J. H. Teall, former Director of the Geological Survey of Great Britain and also of the Museum of Practical Geology, the Geological Society of America has lost one of its most notable foreign members. He died at his home in Dulwich, near London, on July 2, 1924, at the age of seventy-five and a half years.

The scientific career of Sir Jethro embraces two specially important periods. The first was that of most active research, principally in the field of petrology; the second that of Director of the Geological Survey,

[1] Manuscript received by the Secretary of the Society December 29, 1924.

where his own opportunities for investigation were lessened. In this position, however, he contributed from his extensive store of geological information to the work of other men in a remarkable degree, which has been signally recognized.

The period of research must have begun about 1870, when the application of the polarizing microscope to the study of rocks and minerals was still a new method. Unlike many petrographers, Teall did not rush into print with bare descriptive details of the newly discovered characters of rocks. On the contrary, he early showed deep interest in the vital relations between chemical and mineral composition and the influence of varied physical conditions on a crystallizing magma or on a rock undergoing metamorphosis.

In 1883 and 1884 he published a notable series of papers on rocks of the Cheviot District, on a series of dikes in northern England, on the Whin Sill, and, in another direction, on the derivation of amphibole schist from diabase.

In 1888 he completed his major work, entitled "British Petrography," a large volume presenting a comprehensive discussion of known British rocks of igneous origin, from the new standpoint of petrology. It represented a long study by a keen and tireless investigator, far better fitted for such a task than any other of his countrymen. Continental petrologists had advanced much more rapidly than the British in the new science, but through this classic work Teall did much to restore the balance.

It is interesting to note that the original plan of this work included sedimentary and metamorphic rocks in its scope, but the author was obliged to restrict it because of the additional time and expense involved.

Teall's connection with the Geological Survey began in 1888, with his appointment as petrologist. For some years thereafter he was mainly occupied in the office, in the study of material collected by others; but later there was opportunity for field-work and comprehensive reports. After thirteen years of varied service, his ability and wide information were so generally recognized that, on the retirement of Sir Archibald Geikie, Doctor Teall, as he was then known, was chosen to be Director of the Survey.

The personality of the man was most attractive. Tall and slender, swarthy in appearance because of black hair, full beard and large, dark, expressive eyes, he was a striking figure. Genial and kindly in disposition, charming in manner, possessed of a fine sense of humor, he was a delightful companion and friend.

Many honors came to Doctor Teall. He was elected a member of the Royal Society in 1890. After service in several positions in the Geological Society of London, he became its President, 1900-1902. From this society he received the Bigsby Medal in 1889 and the Wollaston Medal in 1905. In 1916 he was knighted and was thereafter called Sir Jethro Teall, using his first given name, that of his father.

He is survived by his wife and two sons, both of whom are in the government service.

SESSION FOR THE PRESENTATION OF SCIENTIFIC PAPERS

The session for the presentation of scientific papers was opened by an address of welcome by Dr. Livingston Farrand, President of Cornell University. An abstract of his remarks follows:

REMARKS BY PRESIDENT FARRAND

Mr. President and Members of the Geological Society of America: There is no duty which falls to my lot more easy and more pleasant to discharge than that of this moment, namely, to bid you a very hearty welcome to Cornell University. We feel here at Cornell that this Society ought to choose Ithaca more often than any other place for its annual gatherings, not only because we want you, but because in a way this was the place of your birth and you would be but fulfilling a certain pious obligation. It is fairly obvious that our wish is not entirely unselfish. We realize that it is Cornell that becomes the chief beneficiary of your deliberations within her walls. No conference such as this can occur without leaving an inspiration of scientific purpose and ideals of permanent value and that we always covet.

I wish we had more to show you by way of provision and equipment in your fundamental field of science. Certainly no one could accuse Cornell of extravagance in its material provision for geology. Possibly you have noticed the way in which we have inveigled you this morning to hold your session under the ægis of a sister science.

It was not to emphasize the contrast between our provisions for the two sciences, but to show you what we hope to do some day for geology. But, after all, it is entirely appropriate that meetings of a geological society should be held in a laboratory of chemistry. The task of science in the search for truth is common, no matter what the term which may be used to denote this or that artificial subdivision of the field of knowledge.

As I came to this building this morning I recalled my own first visit

to Cornell, some twenty-five years ago, on the occasion of a winter meeting of the scientific societies and under vigorous weather conditions not unlike those of today. I could not help regretting the necessity, which mere numbers have created, of holding these sessions independently and thus losing the stimulus which collective gatherings afford. Undoubtedly the greatest contribution of meetings such as this is not in the public presentation of papers, but in the opportunity of contact of minds with minds. For that reason our welcome to you is an eager one, for we shall reap the chief benefit. I need not add that whatever we have is entirely at your disposal, and we sincerely trust that when you leave us it will be with the feeling that your visit has been worth while.

At 10.30 the papers listed on the official program for the Monday morning session were called for.

TITLES AND ABSTRACTS OF PAPERS

WASATCH MOUNTAINS REVISITED

BY ELIOT BLACKWELDER

(*Abstract*)

A third trip to the Wasatch Mountains of Utah and vicinity appears to establish the following results:

1. A new series of pre-Cambrian rocks consisting largely of silvery mica-schists and white metaquartzites. The age is intermediate between the gneisses of supposed Archean age and the quartzite-slate series of the Cottonwood canyons, which is probably late Algonkian. It is probably to be correlated with the rocks of the Encampment, Atlantic Pass, and Medicine Bow districts of Wyoming.

2. Among the Paleozoic rocks there are two very distinct phases. The southern phase is marked by relatively thin formation and many gaps in the sequence. The northern phase is much thicker and more complete. The two phases are separated by the line of the Willard overthrust, mentioned below. The southern phase has its relations chiefly with the stratigraphic sequence in eastern Utah, Wyoming, and Colorado. The northern phase is more closely related to that of Montana, Idaho, and Nevada.

3. The only widespread Tertiary formation—the Salt Lake series of the 40th Parallel Survey—has generally been regarded as Pliocene, and described as consisting of marls and limestones. It contains much conglomerate and volcanic ash, and is considered to be not younger than Miocene and possibly as old as lower Eocene.

4. Tillites and varve slates occur on most of the islands in Great Salt Lake and at several localities along the Wasatch Range, closely associated with the lower Cambrian or uppermost Algonkian. Their age is not yet accurately determinable; they are much younger than the schistose tillites (?) of the early Algonkian in the Medicine Bow Mountains of Wyoming.

5. The Willard overthrust, partially traced in 1909, is a more important feature than at first supposed. The movement was from the west instead of the east as first supposed. It is a folded and faulted sole—probably a detached part of the Bannock overthrust of Idaho, as suggested by Richards and Mansfield. The horizontal displacement can hardly be less than 40 miles, and may be much more. The great displacement may help to account for the remarkable difference in the stratigraphy of the Paleozoic rocks above and below the sole.

6. Cache Valley is not synclinal, as it is represented on all published maps. The beds dip northeasterly and are broken by one or more large normal faults on the east side and smaller ones on the west. These faults are older than the existing topography.

7. Current ideas of the physiographic history of the Wasatch region are open to grave question. The writer no longer feels convinced that the region is one of tilted fault-blocks and alluviated basins in their first (or post-faulting) cycle of erosion.

Read in abstract from manuscript.

Brief remarks were made by Prof. L. D. Burling.

STRUCTURAL NATURE AND ORIGIN OF THE EASTERN ALTAI

BY CHARLES P. BERKEY AND FREDERICK K. MORRIS

(*Abstract*)

The ranges Baga Bogdo, Artsa Bogdo, and Gurbun Saikhan, named in order from west to east, form the eastward extension of the Altai Mountain system. They strike a little south of east, are quite isolated, and out of alignment, each more easterly one stepping to the south. The northerly front of each range rises abruptly along a simple base line. North of each mountain range lies a great basin of sediments ranging in age from Lower Cretaceous to Tertiary. These sediments, in all cases, dip to the south toward the mountains, except for up-drag against the mountain block. This fault displacement represents a series of small movements with long intervening periods of quiescence, the largest movement being of Pliocene or later age. Internally, each of the ranges is complex—each carries strongly folded rocks in addition to metamorphic and igneous formations. The youngest are judged to be of Jurassic age. All are beveled by an upland peneplane. All elevations due primarily to folding had been wholly reduced by long erosion before the present uplift commenced and Lower Cretaceous sediments probably once covered the entire area of each of these ranges. The eastern Altai ranges are, therefore, fault block mountains in which more ancient mountain-folded and complex masses have been lifted to prominent relief.

Presented in abstract extemporaneously by the senior author.

Brief remarks were made by Messrs. Bert S. Butler, Rudolf Ruedemann, and J. E. Spurr, with reply by Doctor Berkey.

TECTONIC HISTORY OF CENTRAL ASIA

BY CHARLES P. BERKEY AND FREDERICK K. MORRIS

(*Abstract*)

All Precambrian rocks are strongly folded. There probably are great unconformities between the T'ai Shan (Archeozoic) injection gneisses and schists and the Wu T'ai Shan (Proterozoic) phyllites, schists and crystalline limestones, and again between these and the greywackes, slates and limestones, which we consider equivalent to the Sinian System (Later Proterozoic) of Grabau. There were at least three ancient mountain-making revolutions of the first magnitude, two of which were certainly Precambrian. The third revolution, which followed the deposition of the greywackes and slates, may have taken place during the early Paleozoic. All three of the older folded systems are cut by immense massifs of the granite of the great Mongolian bathylith. No early Paleozoic rocks are certainly known in the Gobi region, but marine sediments of Permian age were found and others may yet prove to be as old as Mississippian. These are all strongly folded. There may prove to be a post-Permian as well as late Jurassic folding in Mongolia; but in any case a great folding revolution followed the deposition of lower Jurassic sediments of Northern China and of the Tsetsenwan Series of Mongolia which we believe to be approximately their equivalent. All of the mountains so made were reduced to a peneplane by lower Cretaceous time and since that no true folding except along the coast of Siberia seems to have taken place. All the mountains formed since lower Cretaceous seem to be due to warping and faulting. The Kangai and Gangin Daba Mountains represent a vast up-warp with minor faulting. The Altai and its associated system of east-west chains are long narrow fault blocks; in detail each block is a complex of fault blocks rather than a single horst. Large movement seems demonstrable down to latest Pliocene or even to Pleistocene time. Almost certainly the Pleistocene was a period of important mountain growth.

Presented in abstract extemporaneously by Mr. Morris.

PHYSIOGRAPHIC SURFACES IN THE FRONT RANGE OF NORTHERN COLORADO AND THEIR EQUIVALENTS ON THE GREAT PLAINS

BY KIRTLEY F. MATHER

(*Abstract*)

Field studies during the summer of 1924 in north central and northeastern Colorado make possible the following chronologic statement of the principal events in the development of existing topographic forms along the east front of the northern part of the Colorado Front Range.

Subsequent to the crumpling of the Colorado Rockies at the close of Cretaceous time and early in the Eocene period, erosion developed the Flattop peneplane, an undulating lowland above which many monadnocks stood at heights of a few hundred feet. Near the beginning of the Oligocene period, dissection of that surface was made possible by its differential uplift into a broad arch. Sculpturing of the higher portions of the peneplane provided the

materials for the White River and overlying Arikaree or Nussbaum formations which were deposited upon the lower portions of the same graded surface during the erosion cycle which produced the Rocky Mountain peneplane. Remnants of that surface, where it was developed by degradation, rise westward from an elevation of 7,000 feet, along the east front of the mountains in the Livermore quadrangle. Remnants of the Rocky Mountain surface where it was developed by aggradation, decline gently eastward from an elevation of 7,000 feet at the Colorado-Wyoming boundary line, to elevations of less than 5,800 feet, near the northeast corner of the Eaton quadrangle. The construction of the High Plains was largely accomplished during the Rocky Mountain erosion cycle.

Renewal of mountain growth closed that cycle late in the Pliocene or very early in the Pleistocene, and led at first to the deposition of a thin veneer of gravel, the Round Butte conglomerate, which was spread eastward as a piedmont alluvial fan from the upflexed mountain region. Warping was accompanied by regional uplift, and headward erosion soon permitted the east-flowing streams to dissect the deposits just made and cut deep into the rocks beneath. During this third cycle of erosion, which may be named the Alford cycle, wide, flat-floored, late mature valleys were carved in the mountainous portion of the Livermore quadrangle. East of the mountains, extensive gravel-strewn flats were formed. There is no opportunity in the region investigated during 1924 to correlate erosion cycles with glacial episodes, but a long range correlation by analogy with the Quaternary geology of the San Juan mountains leads to the inference that the Alford cycle occupied approximately the first half of Pleistocene time. It was closed by another episode of mountain uplift which permitted the incision of the modern youthful canyons below the mature valleys of the Alford cycle. The canyon-cutting really involved two cycles: an earlier, prematurely terminated cycle, during which many streams reached base level and developed considerable flats by lateral planation in regions of weak rocks; and the modern cycle, in which all but trunk streams in the lowlands are still striving to cut down to grade. The former may be called the Livermore cycle; the latter may be named the Bellvue cycle.

Presented in abstract extemporaneously.

Brief remarks were made by Messrs. F. K. Morris, Andrew C. Lawson, and E. B. Branson, with reply by Professor Mather.

GEOLOGIC MAPPING WITH AIRPLANE PHOTOGRAPHS IN ARIZONA

BY EDWARD SAMPSON [1]

(*Abstract*)

Results of using airplane photographs in an unsurveyed district of strong relief in eastern Arizona. Data for topographic and geologic maps secured in short field season. Methods of work and discussion of applications and limitations of system.

Presented in abstract extemporaneously.

[1] Introduced by G. R. Mansfield.

Brief remarks were made by Messrs. Bert S. Butler, George H. Ashley, and Wilbur A. Nelson.

ADDRESS OF THE RETIRING PRESIDENT OF THE PALEONTOLOGICAL SOCIETY

At this time, 12.15, arrangements had been made in the program for the address of the retiring President of the Paleontological Society, Edward W. Berry, which was then given in general session. Title, On correlation.

With the conclusion of this address, which is published in full in this number of the Bulletin, the session was adjourned for luncheon.

SESSION OF MONDAY AFTERNOON

The afternoon session was opened at 2 o'clock, in the Auditorium, with Past President Schuchert in the chair.

TITLES AND ABSTRACTS OF PAPERS

SUBAQUEOUS TERRACES OF THE GREAT LAKES AND THE SAINT LAWRENCE EMBAYMENT

BY DOUGLAS JOHNSON

(*Abstract*)

Andrews early reported the existence of a terrace 60 feet below water level bordering the shores of certain of the Great Lakes, which terrace he ascribed to wave erosion and utilized it as a measure of post-Glacial time. Others have accepted the 60-foot subaqueous terrace as indicating the depth of wave base on the Great Lakes. Similar submerged platforms bordering the St. Lawrence estuary have been interpreted as wave-cut benches, and cited as proofs of extensive marine abrasion.

Evidence will be presented which seems to indicate (1) that in both these localities the terraces are greater in number and more irregular in their development than formerly supposed; (2) that they are often inclined with respect to present water level; and (3) that they are not the product of wave action, but forms of subaërial origin brought to their present position by partial submergence of a former land surface.

Presented in abstract extemporaneously.

Brief remarks were made by Mr. Frank B. Taylor.

EUSTATIC BENCH IN HAWAII

BY CHESTER K. WENTWORTH AND HAROLD S. PALMER

(*Abstract*)

One or the other of the writers has visited many of the islands of the North Pacific between Longitudes 150 and 180 West and Latitudes 00 and 30 North.

Including the main islands of the Hawaiian group, these number upward of twenty and represent the emergent portions of an area larger than the continental United States or the continent of Europe. On all of the islands visited there are evidences of a higher stand of the sea relative to the land. These evidences include wave-cut benches, notches, and cliffs; coral reef formations and detrital marine rocks,—all now exposed above sea level. The elevation of sealevel indicated by these features is between 10 and 15 feet above present sealevel. Precise determination is difficult because of lack of knowledge of exact former relations of benches, reefs, and accumulated sediments to mean sealevel. Certain islands, notably Oahu, carry also evidence of higher stands of the sea, but these are not considered here. It seems unlikely that epeirogenic movement should affect in such equal degree islands so widely separated as those under consideration, particularly when these belong to at least two morphological units which are not known to be in any way related. It is believed by the writers that the emergence is due to a recent eustatic shift in the level of the sea for which evidence has been found in other parts of the world by Daly and others. No data are in hand for fixing the date of this shift in Hawaii except that it appears to have taken place very recently and that it postdates all secondary recent vulcanism on the island of Oahu.

Presented in abstract extemporaneously by the senior author.

Mr. F. K. Morris asked a question, which was replied to by Doctor Wentworth.

A TROPICAL PEAT BOG

BY CHESTER K. WENTWORTH

(*Abstract*)

In the interior of Washington Island, an emerged atoll of the North Pacific, is a fresh-water lake several hundred acres in extent and three feet above sealevel. The remainder of the area of the former salt lagoon is occupied by a peat bog of nearly equal extent. The arrangement of the vegetational zones around its margin and the presence in the middle of the bog of an "island" of cocoanut palm forest growing on a basement of normal peat indicate that the area is being stabilized and converted into dry land. The peat is three to four feet in thickness, rests on a rolling surface of clean coral sand, and is composed mainly of bullrush stems with very little silt or other rock débris.

Presented in abstract extemporaneously.

WIND-FACETED STONES FROM WYOMING

BY MAURICE G. MEHL

(*Abstract*)

A considerable number of wind-faceted stones have been found scattered over a small area near Riverton, Wyoming. The faceting of some form perfect drei-kanter. The evidence indicates that most of these stones were well

rounded before faceting. It has been possible to determine with a fair degree of accuracy the original size and shape of one of the drei-kanter, a vesicular basalt. The excavation of the lee-side of the vesicles shows clearly the direction of movement of the abrasive that produced the several facets. Some of the larger stones have as many as seven facets and prove that they were shifted during the faceting process.

Presented in abstract extemporaneously.

Brief remarks were made by Messrs. F. K. Morris and Andrew C. Lawson, with response by Doctor Mehl.

EROSIONAL CYCLES IN THE FRONT RANGE OF COLORADO AND THEIR CORRELATION

BY HOMER P. LITTLE

(*Abstract*)

This paper deals with the problem of the erosional history of the Front Range of the Rocky Mountains. The work of Lee in Rocky Mountain National Park, indicating the presence of two main erosion cycles, the Flattop and Rocky Mountain, is accepted and his theory extended to other portions of the range. In addition, the presence of another partial cycle called the Park stage is suggested in explanation of certain of the park areas—especially Woodland, Bergen, and Estes Parks. Occasionally, but not as a rule, remnants of a fourth stage are recognized through minor valley terraces cut within the Park stage. Usually this stage has been removed by headward erosion of the canyons by which all of the streams leave the range. Thus five cycles are recognized within the mountains.

In closing, it is suggested that the Flattop, Rocky Mountain, and Park cycles may be correlated with the Medicine Bow, Sherman, and Leslie valleys cycles respectively, as described by Blackwelder in southeast Wyoming. It is thought that these same cycles are at least roughly equivalent to the Eocene peneplain, summit peneplain, and Boulder Mesa stage, respectively, as described by Atwood and Mather in the San Juan Mountains. Possible correlations with other regions are also indicated.

Presented in abstract from notes.

Brief remarks were made by Messrs. F. P. Shepard, Eliot Blackwelder, and F. K. Morris.

EROSION IN SAN JUAN CANYON, UTAH

BY HUGH D. MISER

(*Abstract*)

The canyon of the San Juan River extends west across a high, arid region in southeastern Utah and joins Glen Canyon of the Colorado near the southern boundary of the state. The region crossed by the canyon is a part of the Colorado plateau, and its general upland surface is composed of several dissected plateaus, each of which is floored by hard rocks. The canyon reveals a

magnificent cross-section of rocks, which, with a thickness of 5,000 feet, range in age from Pennsylvanian to Jurassic. They have been flexed into a broad, gentle arch which is crossed by the canyon, but neither the arch nor the minor structural features have influenced the course of the river. The present course of the San Juan appears to be a striking example of an entrenched meandering stream, which has been largely excavated below the level of a peneplane. That the canyon was rapidly excavated is suggested by the uniformly steep walls on both sides of the river. The process of deepening is still in operation, yet the San Juan is unable to carry during normal stages all the material that is brought to it. High floods, many years apart, scour out much of the deep fill of rock débris, and erosion thus attacks the bed rock floor.

Read in full from manuscript.

COURSE OF THE GUNNISON RIVER IN COLORADO

BY E. B. BRANSON

(*Abstract*)

The Gunnison River's course as related to rock structure is peculiar. Near Delta the stream emerges from the Black Canyon which is cut to a depth of 1,000 to 2,000 feet in igneous rock, while soft shales flank either side. Between Delta and Grand Junction the Gunnison flows in a shallow canyon cut through the Dakota sandstone into the McElmo sands and shales. Bordering the north side of the canyon are the Mancos shales which are exposed in a belt 5 to 10 miles wide. A streamless valley, much lower than the rim of the canyon and down dip from it, parallels the main canyon. The Grand River, for about 25 miles west of Grand Junction, flows on Dakota formation, which dips steeply north. North of the river course the Mancos shales are exposed over wide areas and the expected course would be on the Mancos shales. Through Black Canyon and to the Utah line, the Gunnison and the Grand flow on the hard rocks rather than on the soft, though they seem to have had every opportunity to adjust themselves.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. K. F. Mather, with reply by the author.

POSSIBLE CAUSE OF THE SEMI-ARID CLIMATE OF EASTERN NORTH AMERICA IN TRIASSIC TIME

BY MALCOLM H. BISSELL[1]

(*Abstract*)

The Newark deposits of the Appalachian region are now very generally regarded as having been laid down in intermontane basins under a semi-arid climate with seasonal rainfall. No satisfactory explanation of these climatic

[1] Introduced by George H. Ashley.

conditions has yet been given. Since the present precipitation of the Appalachian region is very largely due to cyclonic storms, the absence or great weakness of these would result in a climate approaching aridity. Evidence is adduced to show that cyclonic storms are related to marked temperature contrasts, and that such contrasts, particularly zonal contrasts, were notably lacking in Triassic times. The aridity of the Newark climates may thus be accounted for. The seasonal rainfall is explainable as a result of monsoon conditions and finds an analogy in eastern Asia today.

Presented in abstract from notes.

Brief remarks were made by Prof. Andrew C. Lawson.

PHYSIOGRAPHIC SIGNIFICANCE OF POST-MIOCENE GRAVELS OF WESTERN SOUTH DAKOTA

BY HAROLD R. WANLESS[1]

(*Abstract*)

In the White River and Cheyenne River basins southeast of the Black Hills the Cretaceous erosion surface is covered unconformably by Oligocene and lower Miocene terrestrial sediments composed mainly of volcanic ash and clastic materials derived from the Black Hills. After the close of sedimentation in this area, the date of which cannot be exactly determined, erosion produced a beveled surface with the general character of a high plain, underlain to the north by Cretaceous sediments, and southward by successively higher beds to the top of the lower Miocene, the upper Rosebud formation. On the remnants of this high plain and in the badland valleys below are to be found large masses of gravels, evidently marking stream channels from which all but the coarsest sediments have been washed away. The gravels consist of igneous and metamorphic rocks, characteristic of the Black Hills, and of sedimentary strata of the Deadwood (Cambrian), Pahasapa (Mississippian), Dakota (Cretaceous), and other Black Hills formations. The bowlders reach a maximum observed diameter of 4 feet at a distance of 50 miles from the foothills of the Black Hills, of 18 inches at a distance of 120 miles, and of 10 inches at a distance of 160 miles. The average size of the bowlders is larger than that observed in any of the Oligocene or lower Miocnee stream-channel deposits of the area. These gravel channels extend in several places across the divide between the White and Cheyenne Rivers and have been observed at many points 10 to 20 miles south of White River. As the Black Hills are now entirely drained by the Cheyenne River and its tributaries, this evidence shows the recent development of the present drainage systems. The wide distribution of large bowlders so far from their source has not yet been satisfactorily explained.

Presented in abstract from notes.

Brief remarks were made by Prof. A. C. Trowbridge, with reply by the author.

[1] Introduced by W. S. Bayley.

PLEISTOCENE BERMUDA

BY ROBERT W. SAYLES AND THOMAS H. CLARK

(*Abstract*)

In January, 1924, a search was made in Bermuda for buried soils indicating interglacial episodes as advocated by the senior author at the 1923 meeting of this society.

Three distinct soils antedating post-Wisconsin time were found at Saint George's Island; three in the Khyber Pass locality five miles south of Hamilton, and at least two and probably three in the city of Hamilton. Two distinct soils were found in several places and further search may reveal three distinct soils in many places. Over fifty soil localities were discovered and samples taken together with many fossils. The fossils are practically all land forms. A few small marine forms blown in by the winds were found. Several small fragments of carbonized wood were also found. Some of the soils have many wind-blown, rounded fragments of foraminifera. Dr. J. A. Cushman concludes that these foraminifera indicate warm waters such as now surround Bermuda. Between the soils is eolian limestone usually from 30 to 50 feet thick, indicative of high winds and a larger Bermuda during each of the dune-forming episodes, which, according to the theory advanced were glacial in character or at least colder and not suited to soil formation. The fossils, according to the junior author, indicate that no rocks older than Pleistocene exist above sea level on the main island of Bermuda.

Evidence of a very recent uplift of the islands or withdrawal of the ocean, of 15+ feet, is afforded by wave-cut benches, sea caves, on the south shore, and, as suggested by the senior author, new stalactites scattered among older ones, in some of the caves. These new stalactites are very thin and from one to five feet long, with an almost continuous thickness of about one-quarter inch, and hollow throughout their length. These have formed since the waters in the caves have subsided enough to leave the roofs bare. The marine waters, with a tidal range of about 2 feet, are still from 20 to 40 feet deep in some of the caves, covering some very large stalagmites which must have formed in a long period when the caves were dry and above sealevel. According to the theory set forth, such a period must have been glacial to reduce the water level of the ocean. At Ireland Island, post-Wisconsin peat 45 feet below sealevel was found, while excavating for the drydock, as reported by Verrill. If the movement of the islands themselves explains a post-Wisconsin subsidence of 100 feet as asked by Verrill, a movement in the reverse direction of 15+ feet is also demanded to explain the sea caves, benches, and new stalactites. On account of finding three buried soils, indicating at least three interglacial episodes, with all the changes of level that these imply, and on account of the improbability of two post-Wisconsin movements of Bermuda in opposite directions, we are of the opinion that Bermuda has remained relatively stationary since the present rocks and soils were formed. The world-wide shifts of ocean level, due to glaciation and deglaciation, first advanced by Charles MacLaren in 1842, and since then advocated by Daly, Nansen, and others, would appear to explain the many changes of level demanded by this theory more easily than so many alternate movements of

the islands themselves. Daly's idea of a recent 20-foot change of ocean level would explain the recent shift of from 15 to 20 feet indicated above, and would accord with the recent apparent uplift of the Bahamas, as shown at Nassau, and also in southern Florida.

Read by title in the absence of both authors.

RECONNOISSANCE OF THE RECESSIONAL MORAINES OF THE FINGER LAKES REGION

BY FRANK B. TAYLOR

(*Abstract*)

This paper gives a résumé of the results of field-work done in 1917, 1921, and 1923. It was found that five moraines of moderate strength, and which had previously been mapped in considerable detail in the Buffalo-Niagara region and eastward to the Genesee River, enter the western side of the Finger Lakes region. Beginning with the youngest and most northerly, they are the Albion, the Niagara Falls, the Buffalo, the Alden, and the Marilla moraines.

The Albion moraine extends along the north border of the eastern part of Cayuga Lake, in which it formed a sharp, narrow tongue reaching a little beyond Aurora. The Niagara Falls moraine, next older and lying a few miles to the south, barely touches the north end of Canandaigua Lake, but extends a long distance up both Seneca and Cayuga lakes. Thence it passes through Auburn and on eastward.

The Buffalo moraine is related to the lake basins in a more interesting way than any of the others. The ice at this stage filled nearly all of the lake basins, all but the four small lakes in the western part of the area—Conesus, Hemlock, Canadice, and Honeoye—and filled each basin to a point beyond the southern end of the present lake. The broad, high ridges between the lake troughs were not covered at this stage, except towards their northern parts, where the ridges are relatively low. Nevertheless, the troughs are so deep that ice-tongues of the most pronounced form pushed far to the south in them and some of them contributed to the building of the great complex valley-head moraines near Dansville, Naples, and Bath, and to the more scattered but similar deposits around Watkins and Ithaca.

The Alden moraine, next earlier than the Buffalo, occurs one mile south of Lavonia at about 1,500 feet, at Townsendville (south of Ovid) at 1,400 feet, and the same five miles west of Ithaca. The Buffalo moraine may reach the lower levels of some of the valley head complexes, but these were built mainly at the time of the Alden moraine and the next earlier, or Marilla moraine. This last moraine was seen only on the high hills east of Scottsburg.

Presented in abstract extemporaneously.

PHYSIOGRAPHY OF THE CALIFORNIA COAST RANGES

BY ROBIN WILLIS [1]

(*Abstract*)

The major features of the Coast Ranges are controlled by movements on the great faults and by deformation of the blocks between. Minor features are controlled in part by faulting and deformation and in part by differential erosion.

The ranges vary widely in age, as shown by the present stage of the topographic cycle. Older ranges show mature topography, controlled by differential erosion. Younger ranges show a mature rolling upland dissected by steep canyons of the later cycle.

Upland surfaces may be simply uplifted or tilted or warped. The type is determined by study of the character of rejuvenation, the profile, and the stream system. Undisturbed old valleys, at high levels, with sharp topographic unconformity indicate simple uplift. Dominance of consequent drainage indicates tilting. The arched profile is developed only by warping. Other criteria are important also in each case.

Any area of uplift may show a variety of these types of surface, often combined with fault scarps. When interpreted these show the relation of tectonic activity to physiography.

Areas of uplift are separated by areas of deposition over depressed blocks, or by valleys along single fault lines. The latter may be due to erosion or to deformation.

The Gabilan Range and its surroundings are used to illustrate the various features mentioned above.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. Andrew C. Lawson, with reply by the author and subsequent further remarks by Professor Lawson.

TOPOGRAPHY OF ACTIVE FAULTING IN CALIFORNIA

BY ROBIN WILLIS [1]

(*Abstract*)

Active faults are expressed in the topography by means of the features due directly to earthquakes, known as rift features, by the larger topographic features produced by long-continued activity on the faults, and by features due to differential erosion along the faults.

Rift features are local and short-lived. They consist of small scarps, undrained ponds, rifts or ditches, and landslides.

The major features due to faulting are *large scarps*, shown by offsets in the older topographic surface, and by discordant development of the cycle in adjoining areas, *fault valleys* due to the downwarping of the surfaces of two

[1] Introduced by Bailey Willis.

adjacent blocks or to a downwarp combined with a scarp, and finally *arched* or *warped surfaces* of the blocks themselves.

Rift features are simulated by local effects of differential erosion, wind ponds, and ordinary landslides. Major features are simulated by erosion scarps and by the differential action of large and small streams.

Erosion features on active faults, especially valleys developed on the shear zone, may be used to trace extensions of faults mapped in part by means of active features.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. D. W. Johnson, with reply by the author.

SPOKANE FLOOD BEYOND THE CHANNELED SCABLANDS

BY J HARLEN BRETZ

(*Abstract*)

The channeled scablands of the Columbia Plateau in Washington are extensive, elongate, denuded tracts of basalt, deeply scored by huge, high-gradient, glacier-born rivers. As physiographic features, the scablands are unique, as were the conditions which produced them.

The above explanation was published a year ago. A crucial test of it, untried at that time, is the character of the Snake and Columbia valleys beyond the scablands, for these valleys received all the discharge of the great glacial rivers during the ablation of the Spokane ice-sheet. If there is no evidence for a greatly flooded condition of these valleys, the hypothesis is wrong and the scabland history must be written in terms of smaller streams and more time; but if these valleys contain such a record, written contemporaneously with the making of the scabland, the hypothesis should stand.

Field evidence indicates that the Columbia River valley below the confluence of Snake River carried a flood which at Wallula Gateway was 2 miles wide and reached 750 feet above present river level, and at Portland was nearly 20 miles wide and 350 feet above present river level.

Read by title in the absence of the author.

With the presentation of this paper the session closed at 5.25 o'clock.

MEETINGS OF MONDAY EVENING

PRESIDENTIAL ADDRESS

At 8 o'clock the presidential address of the retiring President, Waldemar Lindgren, was delivered before the combined societies in the Auditorium of Baker Chemical Laboratory. The title of the address is "Metasomatism," and it is published in full in this number of the Bulletin.

ANNUAL SMOKER

At the conclusion of the presidential address, the members of the Geological Society of America and of the affiliated societies and their friends were invited to participate in a complimentary smoker, given by Cornell University, at Prudence Risley Hall. This was attended by most of the members and gave the first opportunity of the sessions to renew acquaintances and enjoy the social side presented by the meetings.

SESSION OF TUESDAY MORNING, DECEMBER 30, 1924

The morning session was called to order at 9.13 o'clock by President Lindgren, in the Auditorium of Baker Chemical Laboratory, attention being given first to business. The report of the Auditing Committee was called for. The chairman announced that action would be taken on the report of the Council, as distributed in printed form, after the report of the Auditing Committee was presented.

REPORT OF AUDITING COMMITTEE

DECEMBER 30, 1924.

To the Council:

We have checked the vouchers, the record of receipts and disbursements, the bank statement, and the investment record, and we find that they agree with the report of the Treasurer. The securities on deposit in the vault in Baltimore will be examined by a member of this committee and his findings will be duly reported to the Secretary of the Society.

Respectfully submitted,

ELIOT BLACKWELDER,
ADOLPH KNOPF,
JOSEPH T. SINGEWALD, JR.,
The Auditing Committee.

This report was received and accepted, conditioned on receipt of additional report covering the securities.

Joseph T. Singewald, Jr., was delegated to make an examination of the securities of the Society and submit a written report to the Secretary to complete the committee's duties.

REPORT ON SECURITIES

Securities of the Geological Society of America

2 Texas and Pacific Railway Company first-mortgage 5 per cent bonds, numbers 11915, 20892, due June 1, 2000.
2 United States Steel Corporation second-mortgage 5 per cent bonds, numbers 2964, 2974, due April 1, 1963.
2 Fairmont and Clarksburg Traction Company first-mortgage 5 per cent bonds, numbers 29, 30, due October 1, 1938.
2 Consolidation Coal Company first and refunding mortgage 40-year 5 per cent bonds, numbers 11850, 11851, due December 1, 1950.
3 Chicago Railways Company first-mortgage 5 per cent gold bonds, numbers 20750, 20751, 45871, due February, 1927.
2 Southern Bell Telephone and Telegraph Company first-mortgage 5 per cent bonds, numbers M13217, M13218, due January 1, 1941.
2 American Agricultural Chemical Company first-mortgage 5 per cent convertible gold bonds, numbers 5834, 6356, due October 1, 1928.
1 Louisville and Nashville Railroad Company 10-year 7 per cent gold note, number 3941, due May 15, 1930.
1 Commonwealth Edison Company first-mortgage gold bond, number 49652, due 1943.
2 Anaconda Copper Mining Company first-mortgage 6 per cent bonds, numbers M100571, M100572, due February, 1953.
2 American Telegraph and Telephone Company 20-year sinking fund, 5½ gold debenture, numbers 63305, 63306.
2 Baltimore and Ohio Railroad first-mortgage 5 per cent bonds, numbers 41727, 41726, interest certificate, due 1948.
2 Commonwealth Edison 1st collection trust 5 per cent bonds, numbers 8562, 8563.
10 shares Iowa Apartment House Company.
40 shares Ontario Apartment House Company.

The above is a list of the securities in the safe-deposit box of the Society in Baltimore on January 7, 1925.

JOSEPH T. SINGEWALD, JR.

The report of the Council, which had been laid on the table pending the approval of the Auditing Committee, was then formally approved and adopted.

President Lindgren thereupon declared the business closed and announced at 9.18 that the session would be continued for the reading of scientific papers.

WORK OF THE DIVISION OF GEOLOGY AND GEOGRAPHY OF THE NATIONAL RESEARCH COUNCIL

Reports of certain committees working under the Division of Geology and Geography of the National Research Council were introduced by

David White, chairman of the Division, who explained the range of work being undertaken in this manner and called attention to the activity of these committees and the importance of the findings. Reports were presented as follows:

REPORT OF THE COMMITTEE ON SEDIMENTATION

BY W. H. TWENHOFEL

REPORT OF THE COMMITTEE ON PETROLEUM

BY K. C. HEALD

REPORT OF THE COMMITTEE ON TECTONICS

BY WALTER H. BUCHER

REPORT OF THE COMMITTEE ON THE ESTABLISHMENT OF THE PROPOSED GEOLOGICAL ABSTRACT JOURNAL

BY A. C. LAWSON

TITLES AND ABSTRACTS OF PAPERS

PROJECTED OCEANOGRAPHIC INVESTIGATIONS

BY DAVID WHITE

(*Abstract*)

Oceanographic researches planned by the United States Navy Department, supported by other governmental departments but waiting approval and appropriation by Congress, call for very comprehensive, as well as thorough, explorations. Physics of air, sea, and ocean bottom, and some chemical studies of waters and sediments are included in the program. Biology is expected to reach into biochemistry of sediments organic or of organic origin. Chief geologic interest centers in submarine topography, rapidly mapped by Hayes' sonic depth finder; physiography of sea bottom; gravity observations; tectonics and bottomcoring, with study of sediments. The scientific staff is to include geologist and co-operating soil, or biochemist. Ample laboratory space and quarters for a few special volunteer observers are included in proposal.

Presented in abstract extemporaneously.

A NEW FIELD FOR THE GEOLOGIST

BY CHARLES H. BEHRE, JR.[1]

(*Abstract*)

The Commercial Club of Cincinnati has recently established the Resource Survey. The aim of this organization is largely the gathering together of

[1] Introduced by Nevin M. Fenneman.

all available information pertinent to the raw resources which are or may become available for the use of Cincinnati manufacturers. Correspondence with individual mine, quarry, and pit owners and a limited amount of field-work are being used to supplement the data collected from the literature. In the case of certain raw materials, quality tests will be conducted. The results obtained, together with maps and charts, are to be published for general distribution.

This work is not an industrial survey, like that conducted by several municipalities; it differs in its personnel and in its objective, which includes the giving of much attention to theoretical problems in economic geology and geography arising in the course of these studies.

The Resource Survey is conducted by the members of the Department of Geology and Geography of the University of Cincinnati. It began in June, 1924, and now has well under way its work on nine important mineral products or raw organic materials. One report is already completed.

Carried on for a municipality, the conception of undertaking these investigations seems to possess the qualities of energy and foresight. The plan presents to the economic geologist an attractive lane of research and usefulness leading out from his already somewhat circumscribed sphere. Will it mark the beginning of similar work in other cities?

Presented in abstract from notes.

SUBMARINE PHYSIOGRAPHY OF THE GULF OF MAINE

BY DOUGLAS JOHNSON

(*Abstract*)

Studies of sea-floor topography off the coast of Maine, made with the aid of projected profiles based on submarine charts, appear to justify the following conclusions: (1) The "Banks" extending from Nantucket Shoals northeastward toward Nova Scotia and Newfoundland represent a submerged cuesta of the Atlantic Coastal Plain, with which are associated in places at least two minor cuestas, all showing the steep inface and gentle backslope characteristic of such forms. (2) The Gulf of Maine represents the drowned inner lowland separating the "Banks Cuesta" from the oldland of New England. (3) The great breadth of the Gulf is due to the fact that the inner lowland developed on weak coastal plain beds coalesces with a lowland in the oldland rocks developed on weak Triassic beds, as is the case in the inner lowland of New Jersey; the Triassic Lowland of the Gulf of Maine region being traceable far out toward the center of the Gulf. (4) A submarine fault-scarp, sometimes subdivided into two or three minor scarps, can be traced under the water for great distances, separating the submerged Triassic Lowland on the southeast from the crystallines on the northwest. (5) The hills and valleys of the crystalline oldland descend into the Gulf without evidence of extensive modification by wave action at the present sealevel, thus indicating that the sea attained its present level at a time geologically very recent, probably a few thousand years ago. (6) The submergence appears to have been differential, increasingly great toward the northeast; among other lines of evidence, the

edge of the continental shelf, which is nowhere at the traditional depth of 100 fathoms, descends progressively when followed in a northeasterly direction.

Presented in abstract from notes.

Brief remarks were made by Messrs. Sidney Powers, Charles Schuchert, Kirtley F. Mather, David White, Andrew C. Lawson, Edward Sampson, Lancaster D. Burling, and Arthur P. Coleman, with reply by the author.

CRYPTO-VOLCANIC STRUCTURES OF EUROPE AND AMERICA

BY WALTER H. BUCHER

(*Abstract*)

The term "crypto-volcanic" was applied by Branco and Fraas to the Steinheim Basin, a circular depression with a diameter of 1¼ miles in Upper Jurassic limestones of southern Germany. In the center of the basin a hill of Middle and Lower Jurassic rocks appears pushed up to the level of the Upper Jurassic rocks of the undisturbed surroundings. The details of the basin itself are concealed by Miocene lake sediments.

In the United States the writer has mapped two Paleozoic structures which seem analogous to the Steinheim Basin: the Serpent Mound structure in Adams County, Ohio, and the Jeptha Knob structure in Shelby County, Kentucky. Unlike the Steinheim Basin, these are so profoundly eroded as to show the details of structure. They lie in undisturbed plateau sediments, are circular (4 and 2 miles in diameter, respectively), and also show a central portion pushed up in irregular blocks above the normal level, surrounded by a ring-shaped, marginal portion within which the rocks dropped to varying depths below it. No trace of heat effects is seen.

Northeast of the Steinheim Basin lies the Ries Basin, a circular depression over 15 miles in diameter. Its bottom also is largely concealed by Miocene lake deposits, but above it hills of granite and of Triassic and Jurassic rocks rise in jumbled masses.

Drilling has shown that at least at one point the shattered mass of granite lies on younger sediments. On the edge of the basin the original land surface dips gently toward the center and at many places is slickensided, with striations directed down the dip. On this slickensided surface older rocks lie in profoundly shattered masses, thrust outward from the center of the basin. Small quantities of volcanic tuff and bombs are evidence of small, local, volcanic activity which followed the formation of the basin. The detailed studies of Dr. W. Kranz have convinced European geologists that the Ries Basin is the result of "Phraetic Explosion," as E. Suess suggested in 1909. The close association of the Steinheim Basin with the Ries Basin points to a similar origin.

The writer considers it probable that structures of Serpent Mound type are the result of choked phraetic explosion; that is, of explosions at too great depth in proportion to their violence to cause a blasting out of the surface.

Presented in abstract from notes.

Brief remarks were made by Messrs. H. D. Miser, A. R. Crook, and Andrew C. Lawson, with reply by the author.

COMPLEX STRUCTURE IN THE SPRING MOUNTAINS, NEVADA

BY CHESTER R. LONGWELL

(*Abstract*)

The high portion of the Spring Mountain Range has an imbricate structure, with strikes athwart the axis of the range. Six large thrust-faults and overfolds have been found in a distance of 20 miles. Some of the thrusts extend entirely across the range, disappearing under waste on either side. Others terminate abruptly against steep, transverse fractures, on which important differential movement occurred at the time of thrusting. These features appear to have an important relation to the direction of the major deformative forces.

Presented in abstract from notes.

CRETACEOUS AND TERTIARY FORMATIONS OF THE WASATCH PLATEAU, UTAH

BY E. M. SPIEKER AND JOHN B. REESIDE, JR.

(*Abstract*)

The eastern slopes of the Wasatch Plateau are formed by the Upper Cretaceous Mancos shale, thicker in the northern part than heretofore supposed. A sandstone prominent at the southern end of the plateau and previously considered basal Mesaverde is found to be Mancos; it contains the fauna characteristic of the basal zone of the Montana group.

Upon the Mancos shale rests the series of sandy sediments previously called the Mesaverde formation, but here divided into a group of four distinct formations; at base, an intertonguing marine shale and sandstone; next above, a coal-bearing series; then the Castlegate sandstone, a massive cliff-making conglomeratic sandstone; and, at top, a formation of conglomerate, grit, sandstone, and shale containing chiefly fresh-water fossils but with a few brackish-water forms in the basal part.

The abrupt introduction into the series of a new type of sediment—grits and conglomerates—supported by at least local evidence of unconformity at the base of the Castlegate shows a marked change in conditions of origin and suggests a later age than typical Mesaverde. The fossils from a horizon immediately above the Castlegate sandstone connect it most closely with the Fruitland and Kirtland formations of the San Juan Basin of northwestern New Mexico, believed to belong to the uppermost part of the Montana group. The fossils, however, also connect the formations with the Laramie formation of Denver Basin and the Lance formation, post-Montana in age. The writers believe the beds to be Cretaceous and probably of the age of the Fruitland and Kirtland formations.

The boundary between Cretaceous and Tertiary is held to lie not higher than the lowest red and varicolored sediments, which are considered to be

derived from the brilliantly colored Triassic and Jurassic rocks uptilted farther west during the orogenic disturbance that is taken to mark the passage between Cretaceous and Tertiary time and which are assigned to the Wasatch formation. On the west side of the plateau the Price River rocks were clearly involved in the disturbance, the Wasatch not. At many places a conglomerate, whose pebbles are largely fresh-water limestone of the types regionally peculiar to the Wasatch formation, marks the boundary. Beds of the age of the Lance and Fort Union or equivalent formations are believed to be absent.

The Wasatch formation contains a remarkable member of fresh-water limestone, 200 to 1,000 feet thick, called the Flagstaff member, for which no origin other than chemical or bacterial precipitation seems possible. It contains the fresh-water fauna found generally in the Wasatch formation of surrounding regions and also several beds made up almost exclusively of ostracods.

In later Tertiary time the region underwent considerable tensional disturbance, with the formation of pronounced zones of normal faults and cognate monoclinal folds, the results of which are superposed on the older, compressional structures, which are restricted to the western border of the plateau.

Read in full from manuscript by the senior author.
Brief remarks were made by Prof. Charles Schuchert.

ORIGIN OF THE SANTA LUCIA COAST RANGE, CALIFORNIA

BY PARKER D. TRASK [1]

(*Abstract*)

The history of the Santa Lucia Range includes the following stages:

(1) Extensive faulting involving beds probably of Pliocene age.
(2) Development of an old-age erosion surface.
(3) Warping and faulting of this surface.

Read in abstract from manuscript.
Brief remarks were made by Mr. Robin Willis.

TUFF CRATERS OF OAHU

BY CHESTER K. WENTWORTH

(*Abstract*)

The pyroclastic craters of southeast Oahu are divided into six principal groups and include over thirty separate vents. Palagonitic tuff is the principal material, but in addition there are considerable quantities of black ash and basalt from small fissure vents associated with the tuff. The total amount of material extruded from these craters at many different times is conservatively estimated at about two cubic miles. Comparing this amount with the six cubic miles estimated by Griggs for the Katmai eruption in 1912, it is apparent that any single one of the eruptions of southeast Oahu must have

[1] Introduced by H. E. Gregory.

been of far lesser magnitude than the Katmai explosion. The number and accessibility of these craters from Honolulu and their proximity to the sea-coast, where they have been extensively eroded, have facilitated a detailed study of their structure, lithology and history. Conclusions reached by the writer in regard to the durations of the several eruptions are in substantial agreement with those of Sereno Bishop, who argued many years ago for the brevity of tuff cone eruptions. It is believed that the formation of each of the simple craters took place in a few days at most and perhaps occupied but a few hours.

Presented in abstract from notes.

THRUST-FAULTING IN THE MOUNT DIABLO REGION OF MIDDLE CALIFORNIA

BY BRUCE L. CLARK

(*Abstract*)

The most conspicuous known structural feature in middle California is the Mount Diablo thrust. This represents a typical Alpine structure, a fault with a dip averaging between 6 degrees and 5 degrees. The thrust has a minimum throw of approximately 10 miles. Mount Diablo, which has an elevation of about 3,800 feet, is cut on its south side by this thrust, at an elevation of about 2,000 feet, the thrusting coming out on the north side, thus completely cutting through the mountain. The formations above the thrust are of Franciscan (Jurassic ?) age; the beds below are of Cretaceous age. The Franciscan series appears to have been faulted up into the Cretaceous before the major thrusting which produced the Mount Diablo thrust. Thus, on either side of Mount Diablo we find the thrust-plane cutting into the Cretaceous which practically surrounds the Franciscan mountain mass above the thrust. The front of the thrust, due to its low dip and erosion, is sinuous. The plane is offset by many cross-faults. One major cross-fault has caused an offset of four miles. The fault-plane is warped along the east-west axis and north-south axis. The hard, metamorphic rocks at the top of Mount Diablo rest in a synclinal trough produced by this warping. To the west of the mountain the thrust-plane is folded so that it produces broad structural valleys on two sides of a range of hills over which it arches and on the tops of which are erosional remnants from above the thrust-plane.

In the Byron Quadrangle a number of major upthrusts have been mapped. One of these cuts out 2,000 feet of Oligocene from an area, as mapped, of over 6 miles along the strike. Another cuts out about 1,500 feet of the Eocene. The Mount Diablo thrust is very closely connected with the folding, which is intense in places. The Tertiaries to the south and below the plane are much more folded and faulted than those above. Those above, especially the Cretaceous and Tertiary rocks, dip in one general direction—to the north.

Presented in abstract extemporaneously.

Brief remarks were made by Messrs. Andrew C. Lawson, Waldemar Lindgren, and Robin Willis, with reply by the author.

At this point, 1 o'clock, the session was adjourned for luncheon.

SESSION OF TUESDAY AFTERNOON

The afternoon session was opened at 2 o'clock in the Auditorium of Baker Chemical Laboratory, Past President Charles Schuchert presiding, and proceeded immediately to the reading of scientific papers.

TITLES AND ABSTRACTS OF PAPERS

PROBABLE CORRELATION BETWEEN THE LAST ICE-RETREAT IN NORTH AMERICA AND IN EUROPE[1]

BY ERNST ANTEVS[2]

(*Abstract*)

The best estimates of the time that has elapsed since the last retreat of the ice from the Niagara Falls region, Toronto, southern Sweden, and the Alps indicate that the two largest ice-sheets disappeared at the same time. The chief cause may have been rise in temperature. The supposition of contemporaneity is supported by other conditions. Thus, the warm period in North America a few thousand years ago almost surely was contemporaneous with the temperature maximum in Europe, estimated by Ragnar Sandegren to have prevailed during the time from 7,000 to 2,500 years ago. The large growth in thickness of *Sequoia washingtoniana* in California during the fourteenth century was probably connected with the contemporaneous cold and stormy spells in the Old World, known by historical records. At present there is an intimate relationship between the atmospheric centers of action as shown by H. H. Hildebrandsson. The summer temperature north of the Great Lakes is usually low when high in North Europe, and *vice versa*, while the summer temperature in the States east of the Rockies in many instances follows that of north Europe. If the North American and the European ice-sheets disappeared at the same time and for the same reason, New England in regard to the uncovering should correspond to northern Germany, and Canada to the Scandinavian countries. The belt across Lake Champlain and the Province of Ontario, between Lake Ontario and the Mattawa River, should approximately correspond to the Danish Islands.

The uncovering of northern Germany is not chronologically studied, but series of morainic lines indicate repeatedly interrupted recession, not dissimilar to that which took place south of the Great Lakes and in New England. In the zones north of Lake Ontario and in Denmark the longest interruptions occurred in the ice-retreat, which otherwise was rather rapid or only intercepted by comparatively short halts. They seem to form the natural starting points for attempts to connect events in the two continents. The release of the Mattawa Valley and the beginning of the Nipissing Great Lakes, which marks about the end of the relative stagnancy of the ice edge and the beginning of rapid retreat, according to F. B. Taylor's time estimates, based upon the cutting of the upper sections of the Niagara Gorge, occurred about 10,000

[1] Published by permission of the Director, Geological Survey of Canada.
[2] Introduced by Jay B. Woodworth.

to 11,000 years ago. The uncovering of central Scania, the southernmost province of Sweden, which initiated rapid retreat in Europe, happened about 13,500 to 14,000 years ago, according to De Geer's and Ragnar Lidén's studies. The uncovering of the region between Lake Ontario and the Mattawa River, which corresponds to the Kirkfield and the Port Huron-Chicago stages of Lake Algonquin and to the cutting of the Old Narrow Gorge and the Lower Great Gorge by the Niagara River, probably required between 10,000 and 15,000 years. The ice-retreat from the Danish Islands and southwestern Scania was very complicated. There seems to have been a large oscillation after the release of northeastern Zealand, a somewhat less fluctuation during the uncovering of central Zealand and southwestern Scania, and a third probably large oscillation (after the Alleröd period), when the ice retired in southeastern Scania. Besides, there were many minor oscillations recorded by moraines, etc. Although insignificant as far as the movements of the ice edge go, several of these latter oscillations represent very long periods of time, even more than 1,000 years. The whole uncovering may have taken about as long a time as that of southern Ontario. The next most marked interruption of the ice-retreat in Europe north of Germany is that during which the Fenno-Scandian moraines, or the morainic belt across southernmost Norway, central Sweden, and southern Finland was formed. The halts began about 2,500 years after the ice-retreat had started in central Scania. In Finland, where the moraines and their deposition have been most carefully studied, there occurred two marked halts separated by slow retreat representing, according to Matti Sauramo, in all 659 years. In Canada, 1,800 to 1,900 years after the mouth of the Montreal River on Lake Timiskaming became free from ice, a series of partly marked halts and readvances took place. The rate of the ice-retreat between the Mattawa Valley and the mouth of the Montreal River is unknown, but the halts north of Matheson occurred about an equally long time after the ice border left the Mattawa Valley as did the Fenno-Scandian halts after the beginning of the recession in central Scania. The oscillations in Canada represent a longer time than those in Scandinavia. However, exact agreement is not to be expected, for, even if the cause of the oscillations was the same, its effects were likely influenced by regional conditions such as nourishment, topography, etc. The correlation outlined is the only one that, with the present knowledge of the waning of the ice-sheets, can come into consideration.

Presented in abstract from notes.

Brief remarks were made by Messrs. Arthur P. Coleman and Frank B. Taylor.

PLEISTOCENE PRE-WISCONSIN BEDS IN VERMONT

BY ERNST ANTEVS[1]

(*Abstract*)

Three miles south-southeast of Newport, Vermont, the following section was exposed in 1921:

[1] Introduced by Jay B. Woodworth.

1. Topmost, 3 feet till.
2. 4.5 feet glacial varved clay, about 30 varves, the top 10 varves somewhat disturbed and slightly weathered.
3. 1.5 feet till.
4. 10 feet brown, glacial, varved clay, the upper 9 feet disturbed and faulted; the lowest 14 inches contain 12 partly contorted varves, the uppermost 3 feet being strongly weathered.
5. 20 feet till to brook level.

The upper till bed, which unquestionably occurs in original position, may mark an oscillation of the ice-front. Between the deposition of the lower clay (Bed 4) and the second till (Bed 3) there must have been a time interval of thousands of years during which the clay was exposed to weathering. How to account for so long an interval is not clear. Wisconsin oscillations seem to be inadequate. Perhaps this clay bed 4 belongs to a pre-Wisconsin sheet.

Read by title.

GLACIAL LAKE HACKENSACK AND ADJACENT LAKES

BY CHESTER A. REEDS

(Abstract)

The existence of glacial Lake Hackensack immediately following the Wisconsin ice-sheet is shown by laminated and varved clays, of which 2,550 were counted in 1923. Subsequent field-work indicates that the total number may be doubled. The plotting of the data shows a general agreement with the isobases for eastern North America and with the results obtained from the study of Lake Passaic immediately west of Lake Hackensack.

Presented in abstract extemporaneously.

THE KANKAKEE TORRENT

BY GEORGE E. EKBLAW AND L. F. ATHY[1]

(Abstract)

Heretofore the Pleistocene sediments in the Kankakee River basin have been interpreted as indicating the existence of a lake, known as Lake Kankakee, during the Wisconsin glacial epoch. Recent studies in the Kankakee and Essex, Illinois, quadrangles have brought to light evidence that, instead of normal lacustrine conditions, a combination of torrential and quiet water conditions prevailed. This paper will present not only the new evidence which has accumulated, but also a consideration of the variety of conditions effected by the torrent over a wide area, and of the time relations involved.

Read in abstract from manuscript by the senior author.

[1] Introduced by M. M. Leighton.

STRUCTURAL GEOLOGY IN THE MID-CONTINENT REGION: A FIELD FOR RESEARCH

BY SIDNEY POWERS

(*Abstract*)

Structural geology offers a new field for research in the Mid-Continent region where Paleozoic and younger formations are studied in minute detail by means of the thousands of wells which have been and are being drilled through them. Structure at the surface is mapped by plane-table work, supplemented by test-hole drilling for structure, by studies of soil, and by well water analyses. Structure underground is determined by comparison of logs and cuttings of wells.

Instead of the uniformatarianism which is supposed to characterize the central portion of the United States, most complicated disconformities and unconformities are revealed. Folding is of neither the Appalachian nor the Rocky Mountain type, but is what may be called the Plains type. The Paleozoic sediments were deposited on a peneplaned surface of low, but abundant, relief. The topographic hills are now buried hills. After successive periods of sedimentation they were rejuvenated, so that they are invariably overlain by an anticlinal type of folding which, however, is gradually modified and even disappears where the overlying section is over 2,500 feet thick. Size and magnitude of folding are proportional to distance above the pre-Cambrian floor, not to distance from major regional uplifts. Faulting is probably concentrated in echelon lines in different horizons, dying out both above and below as well as laterally.

Read in abstract from manuscript.

Brief remarks were made by Messrs. A. C. Hawkins and Hugh D. Miser.

SOME TRANSVERSE FAULTS ALONG THE ROCKY MOUNTAIN TRENCH

BY F. P. SHEPARD[1]

(*Abstract*)

Structural sections are usually made across mountain ranges, rather than parallel to their axes. In the case of the Rocky Mountain Trench, a section along the bordering ranges can be made without difficulty. A comparison of this section with sections made across the ranges to the east shows a marked contrast. The east-west sections are typified by isoclinal folds, thrust-faults, and crumpling. The north-south section contains a series of monoclinal fault blocks dipping predominately to the north at rather low angles, with the faults running in general transverse to the Rocky Mountain Trench. The faults are thought to have dominantly horizontal displacement with only apparent vertical offset.

Presented in abstract extemporaneously.

[1] Introduced by T. E, Savage.

ACTIVE THRUST-FAULTS IN SAN BENITO COUNTY, CALIFORNIA

BY PAUL F. KERR[1] AND HUBERT G. SCHENCK

(*Abstract*)

An account of the structural features that accompany the San Andreas Fault in the California Coast Range. The paper deals with two different systems of thrust blocks. One, west of the San Andreas Fault, extends from the granite bathylith of the Gabilan Range through Oligocene and Miocene sediments to the San Benito Valley; the other, east of the fault, extends for about 25 miles in the opposite direction. The latter produces striking topographic features in Pleistocene sediments of unusual thickness and shows evidence of extensive recent faulting. Special reference is made to rift features and areas of slumping due to active faults in soft Pleistocene strata.

Presented in abstract extemporaneously by the senior author.

Brief remarks were made by Prof. Andrew C. Lawson, with reply by Professor Kerr.

TACONIC FOLDING IN PENNSYLVANIA

BY BENJAMIN L. MILLER

(*Abstract*)

Belief in an important period of folding near or at the close of the Ordovician period seems to be passing away and instead we are told that at that time there was only "slight local folding in southeastern New York, New Jersey, Maine, and New Brunswick." Whether the evidence for the "Taconic revolution" has been unduly minimized in New York, New England, and southeastern Canada is a question. In the recent discussions Pennsylvania has been overlooked, although the State seems to present better evidence of extensive changes at this period than any of those mentioned.

Marked unconformities exhibited in the cuts where the Delaware, Lehigh, and Schuylkill rivers break through Blue Mountain indicate strong folding and subsequent erosion of the Martinsburg shales before the deposition of the basal conglomerates of the Shawangunk. Unoriented, sericitized fragments of Martinsburg slate are present in the basal beds of the Shawangunk. The greater complexity of structure and more metamorphism of the Cambro-Ordovician sediments in comparison with the Siluro-Devonian strata of the region furnish additional evidence of Taconic movements.

Read in abstract from manuscript.

TACONIC FOLDING IN THE MARTINSBURG SHALES[2]

BY CHARLES H. BEHRE, JR.[3]

(*Abstract*)

Recent detailed studies of the Ordovician Martinsburg shales of Lehigh and

[1] Introduced by Charles P. Berkey.
[2] Presented with the permission of the State Geologist of Pennsylvania.
[3] Introduced by George H. Ashley and B. L. Miller.

Northampton counties, Pennsylvania, have yielded evidence for the following three clearly separable periods of movement affecting these rocks: (1) thrust-faulting with tiny overfolds; the axes were inclined at high angles to cleavage planes now seen in the slate; the folds suggest extreme plasticity of the deformed material; (2) intense compression with development of slaty cleavage in the shales and of minor faulting in the intervening competent beds; (3) compression from the same directions as in Movement Number 2, resulting in relatively "open" faults along bedding planes and in the crumpling of the slaty cleavage developed by Movement Number 2. In addition great overthrust faults of either Taconic or Appalachian age and lesser, "tight," apparently relaxational faults, are seen but can not be chronologically placed with certainty.

The latest of the three periods of movement must be of Appalachian age, no later deformative epoch being known for this region. The middle movement is thus pre-Appalachian. As there is a marked unconformity between the Shawangunk and the underlying Martinsburg, this middle movement and the development of slaty cleavage are probably to be assigned to the Taconic. A comparison of the effects of this with those of the Appalachian uplift in the region suggests that the Taconic was here almost if not quite as violent as the Appalachian revolution.

Presented in abstract extemporaneously.

At the conclusion of this paper, time was given for discussing this and the preceding paper by B. L. Miller. Remarks were made by Messrs. H. B. Kummel, I. C. White, George H. Ashley, H. F. Cleland, Charles Schuchert, James F. Kemp, H. N. Eaton, Bradford Willard, and U. S. Grant, with reply by the authors.

CENTRAL ASIA IN CRETACEOUS TIME

BY CHARLES P. BERKEY AND FREDERICK K. MORRIS

(*Abstract*)

All available literature bearing upon the distribution of Cretaceous deposits in northern Asia has been reviewed and the data plotted upon a summary map. There is indicated a shallowing of the late Jurassic Sea in the Himalaya trough, followed by a broad advance of the marine Cretaceous, which spread as far north as the Aral Sea in western Asia.

Marine Cretaceous beds of a near-shore type are known in Japan and Sakhalin, but westward the next Cretaceous beds are of Continental type, as seen in Shantung and on the Amur River. In Jehol and Kansu there are fish-bearing shales that may be Lower Cretaceous but are at present called Upper Jurassic by most authorities.

The Third Asiatic Expedition found at least three horizons: the Oshih-Ondai Sair, called by us Lower Cretaceous; the Djadochta, and the Iren Dabasu, regarded as Upper Cretaceous.

The Oshih and Ondai Sair are of much the same type as the fish-shales of

Kansu and Jehol, and these compare in turn with fish-shales reported in Siberia. All together they doubtless represent a chain of inland basins developed under a dominantly moist and warm climate and probably upon a low-lying country.

The fauna includes several genera of primitive Ceratopsians and an Ankylosaur, which have remote, perhaps ancestral, relations to the American Cretaceous fauna, but seem to have little or no relation to the faunas of Europe or Africa. The Amur River beds carry trachodont remains. No undoubted Cretaceous rocks have been reported north of this region to the Arctic Ocean, unless it be the fish-shales of Transbaikalia.

The evidence of isolation in all the faunas thus far studied suggests a partial confirmation of Borissiak's inference that there was a sea barrier between Europe and Asia during Cretaceous time. We may picture Asia in Cretaceous time as a vast and relatively stable continent that has suffered no subsequent movements save folding along the extreme eastern margin and block-faulting in the interior.

Presented in abstract from notes by Mr. Morris.

Brief remarks were made by Messrs. Walter H. Bucher and Charles Schuchert, with reply by Mr. Morris.

TWO NEW VOLCANIC ASH HORIZONS IN THE STONES RIVER GROUP OF THE ORDOVICIAN OF TENNESSEE

BY WILBUR A. NELSON

(*Abstract*)

The paper describes the occurrences in east Tennessee of these two new bentonite horizons occurring in the Stones River group, at the base of the Ordovician. Data are presented on the presence of an ancient landmass extending under the Cumberland Mountains in the Cumberland Gap regions of Tennessee and Kentucky. Analyses of the two new bentonite horizons are given.

Read in abstract from manuscript.

PRECAMBRIAN GEOLOGY NORTH OF LARAMIE, WYOMING

BY J. F. KEMP AND S. H. KNIGHT

(*Abstract*)

In the summer of 1923 the authors spent five weeks in the area and have amplified their observations since then. The area studied lies to the north of one already mapped on the south in the Laramie folio of the U. S. Geological Survey by Professor Blackwelder, but was studied in part still earlier by the authors. The pre-Cambrian forms the core of the Laramie range. It is an area of rolling country with some steep hills. It is bordered by Pennsylvanian strata, which rest unconformably on it.

The oldest rocks are quartzites, limestones, and amphibolites, which appear chiefly as xenoliths of great size and extent in the intrusive granite. Features

of contact metamorphism and lit-par-lit injection will be described. The oldest intrusive is anorthosite, which has associated with it titaniferous magnetite, of which several new exposures have been discovered. A norite followed; and, lastly, very extensive granite closed the igneous activity. Some petrologic features of interest will be briefly outlined.

Presented in abstract extemporaneously by the senior author.

Brief remarks were made by Prof. Eliot Blackwelder.

THE COUTCHICHING PROBLEM

BY FRANK F. GROUT

(*Abstract*)

The formation named Coutchiching by Lawson is a mica schist, supposedly sedimentary and supposedly underlying Keewatin greenstone. Detailed mapping of structure in two critical areas in Minnesota has led to the conclusion that there is no such formation in the State, even on the shores of Rainy Lake, near Koochiching Falls, whence the formation takes its name.

Before publishing such a conclusion, it has seemed best to make a reconnaissance over several areas on which Lawson based his conclusion that sediments lie below greenstone. This has now been done. At Bear's Passage the structure shows mica schist to be younger than greenstone. From Shoal Lake to Atikokan the mica schists lie above the Seine (Huronian) conglomerate. These areas thus give no support to the Coutchiching hypothesis.

The strongest evidence of a pre-Huronian sediment is on Rice Bay of Rainy Lake, where sedimentary mica schist is interbedded with hornblende schists. Here both rocks are of uncertain age. Their structure is determined only with difficulty, the beds are crumpled and the sedimentary schist aggregates probably less than 500 feet in thickness. As it alternates with greenstone and its base is not known, it seems better to consider it a phase of Keewatin than to give it a formation name.

Presented in abstract extemporaneously.

Brief remarks were made by Prof. Andrew C. Lawson, with reply by the author and subsequent remarks by Professor Lawson.

TRIASSIC SEDIMENTARY ROCKS AND BASALTIC FLOW NORTHWEST OF LEBANON, PENNSYLVANIA

BY GEORGE W. STOSE AND ANNA I. JONAS

(*Abstract*)

An outlying area of Triassic sediments about four miles wide has been discovered 10 miles northwest of the main area of Triassic rocks near Lebanon, Pennsylvania. The beds are composed of greenish-yellow medium-grained arkosic sandstones and soft red and buff shales and include an interbedded basaltic lava flow. They lie on Ordovician shales and have not heretofore been separated from them; the basaltic flow which is interbedded in these

rocks was also assumed to be of Ordovician age. The sedimentary rocks of this new area have many of the lithologic and structural characteristics of the Triassic sandstone and shales of the main belt. The beds are in general not folded but dip gently southward and occupy a tilted fault-block, dropped down along a normal fault on its south side. The lava flow corresponds in stratigraphic position with all the other known occurrences of Triassic lavas of Pennsylvania and New Jersey. They occur in the latest Triassic sediments and are preserved chiefly in synclines on the northwestern down-dropped side of fault-blocks. The basalt was poured out near the end of Triassic sedimentation, just before the period of block faulting which terminated the Triassic.

Read by title in the absence of the authors.

DISCOVERY BY GEOPHYSICAL METHODS OF A NEW SALT DOME IN THE GULF COAST

BY E. DE GOLYER

(*Abstract*)

This paper gives the results of a gravity survey by Eotvos torsion balance of an area in southeastern Texas, with comparative results of a similar survey of the Spindletop Dome and a description of the salt dome discovered by subsequent drilling.

Presented in abstract from notes.

Brief remarks were made by Prof. Waldemar Lindgren.

AN UPPER CRETACEOUS DISCONFORMITY IN ALBERTA

BY J. A. ALLAN AND J. O. SANDERSON

(*Abstract*)

A disconformity between the Edmonton and Paskapoo formations has been discovered and mapped over an area of about 3,000 square miles, in central Alberta. The Edmonton formation corresponds to the uppermost Cretaceous, the Paskapoo is younger and has been regarded as Lower Tertiary in age, and correlated by some with the Lance and the Fort Union.

Further evidence has been obtained that whereas the strata in the younger formation are generally conformable with the older, yet much of the older was removed by erosion before the deposition of the Paskapoo. The thickness of the strata removed from the Edmonton varies from zero to 450 feet, where the contact has been definitely observed. It is anticipated that further study of this interformational break will disclose the true relationship between these two formations, and will probably give definite information on the much discussed Cretaceous-Tertiary contact.

Read by title in the absence of both authors.

A REMARKABLE ADIRONDACK GLACIAL LAKE

BY WILLIAM J. MILLER

(*Abstract*)

A recent examination of the Hudson-Schroon valleys of the southeastern Adirondack region has furnished evidence that a remarkable long, narrow glacial lake lay in those valleys during the waning of the last great ice-sheet in northern New York. The lake was nearly 65 miles long, and it reached a width of as much as two miles in but few places. The most prominent branches of the lake reached into the Sacandaga Valley, between Luzerne and Conklingville, into the Hudson Valley between Warrensburg and The Glen, over the sites of Chestertown and Loon Lake, and over the site of Paradox Lake. The writer's previously described Glacial Lake Warrensburg and Glacial Lake Pottersville, and Stoller's still more recently described Lake Corinth, are believed to have been but parts of the single, long, narrow lake which it is here proposed to call Glacial Lake Warrensburg. The waters of Lake Warrensburg were ponded by an ice blockade of the waning Champlain-Hudson lobe of ice in the vicinity of South Corinth and Corinth. Due to post-Glacial tilting of the land, the wonderfully preserved lake deposits rise with a fair degree of uniformity from an altitude of somewhat less than 700 feet on the south, to about 1,000 feet on the north, or at the rate of over four feet per mile.

Read by title in the absence of the author.

OUR MISSING PERMIAN

BY CHARLES R. KEYES

(*Abstract*)

Whether or not we have in America anything corresponding to the typical marine Permian rocks of eastern Russia is still as moot a question as it was three-quarters of a century ago, when Jules Marcou announced the finding, in the southwest, of Permian types of fossils.

In the Guadalupe Mountains of the Trans-Pecos Texas, there is a thick section of limestones, the faunas of which more resemble those of the Urals than any that we have in this country. Unusual interest should therefore center on this Guadalupian series. From what is known of its present stratigraphic position it probably once extended far northward in the Rocky Mountain geosyncline, perhaps to Alaska and possibly across Asia and on into eastern Europe to the Province of Perm. If it did, it long since was removed during the successive planations of the ancestral Rockies. No less than ten of these erosion intervals are now known. The planation which immediately preceded the deposition of the Cimarronian red beds alone removed a mile of thickness of Guadalupan beds, in Colorado quite down to the pre-Cambrian complex.

Remnantal patches may yet be found within the Cordilleran tract. We should search for the Guadalupan rocks far south of the New Mexican boundary, in Trans-Pecos Texas, and in Old Mexico.

Read by title in the absence of the author.

STRUCTURAL FEATURES OF NEW MEXICO AND ARIZONA

BY N. H. DARTON

(*Abstract*)

In studying the geology of various portions of New Mexico and Arizona for geologic maps of those States now in course of publication, many data have been obtained as to the structure, especially of the mountain ranges and great plateaus. These comprise faulted and tilted blocks and numerous flexures of considerable extent. Some of the uplifts have limited the areas of deposition at various times and resulting overlaps have an important bearing on the stratigraphy and classification. The more striking physiographic features are closely related to the structure, although in both States the volcanic rocks form some of the most prominent mountains.

Read by title in the absence of the author.

At this point, 6 o'clock, the session was adjourned.

ANNUAL DINNER

At 7 o'clock the Society and its visitors and guests, together with the members of the Paleontological Society, the Mineralogical Society of America, and the Society of Economic Geologists, assembled in the dining room of Prudence Risley Hall for the annual dinner. There was an attendance of more than 200, and the appointments of the room proved to be exceptionally suitable to the purpose. The comfortable surroundings and good service, together with the entertainment of the after-dinner program, provided an exceptionally enjoyable evening.

President Lindgren spoke briefly of the conditions under which the meetings of the Society are being held, and recalled that two of the affiliated societies—the Paleontological Society and the Mineralogical Society—were presenting programs, and although the Society of Economic Geologists was not presenting a program at this meeting, its members were present in considerable number and had an important presentation to make at this time. He then introduced Prof. James F. Kemp, President of the Society of Economic Geologists, who presented to Prof. T. C. Chamberlin the medal given for the first time by the Society of Economic Geologists as a mark of exceptional service in the advancement of the science of geology. A slight accident to Professor Chamberlin, late the previous afternoon, prevented his attendance; but he was within reach and the medal was received by Prof. Stuart Weller in his name.

President Lindgren introduced Professor Kemp as toastmaster, who prefaced his remarks with references to the early days of the Society, referring particularly to the service of the late Prof. H. S. Williams, at

whose invitation the first sessions were held at Cornell. He finished his remarks on this topic by reading a letter from the son of Professor Williams, whose position as one of the trustees of Cornell University gave particular point to his letter of welcome to the Society.

Professor Kemp then stated that of the thirteen who met December 27, 1888, and completed the organization of the Society, three still survive, namely, I. C. White, H. L. Fairchild, and himself. He then called on Dr. I. C. White for reminiscences connected with the organization. Doctor White's recollections of the sessions (December 27-28, 1888) were intensely interesting and particularly appropriate. The note of wistfulness, as he spoke of early days, and the touch of uncertainty as to other returns to Cornell gave an added charm to his words and measurably strengthened the bond of affection that has been growing with the years for the founders of the Society. Professor Kemp, who had been also at the meeting of Section E of the American Association in Cleveland, August 14, 1888, recalled its proceedings and added a few other historical facts going back to a time several years earlier.

The following speakers were then called on and gracefully responded: E. W. Berry, for the Paleontological Society; Henry S. Washington, for the Mineralogical Society of America; H. B. Kummel, for the State Geologists; John M. Clarke, for the "firm" of Hall and Clarke, continuously in office for a century; Heinrich Ries, for Cornell University, the host of the Society, and Andrew C. Lawson, for the Pacific Coast geologists.

Session of Wednesday Morning, December 31, 1924

The regular session of Wednesday morning was called to order at 9.20, with Past President Schuchert in the chair.

TITLES AND ABSTRACTS OF PAPERS

REYNOSA FORMATION IN SOUTHWEST TEXAS

BY A. C. TROWBRIDGE

(*Abstract*)

Within the Reynosa formation as now defined are included the limestone and conglomerate unconformably overlying Miocene strata at Reynosa, Mexico, described by Penrose in 1890, the thick, gulfward-dipping formation of limestone, conglomerate, gravel, sandstone, sand, and clay which outcrops in a wide belt parallel to the coast from Rio Grande to east Texas and lies unconformably on Upper Eocene, Oligocene, Miocene, and Pliocene formations,

described by Dumble in 1918, Trowbridge in 1923, and Deussen in 1924, and the outlying patches of upland gravel and conglomerate on the landward side of the main outcrop, described by Hill and Vaughan in 1898 as the Uvalde formation. These sediments make up the youngest Tertiary formation of the west Gulf Coast and underlie unconformably clastic sediments of Pleistocene age. They were included in the Lafayette of McGee and are about the same age as the Pliocene Citronelle formation of east Texas, Louisiana, Mississippi, and Alabama.

Field investigation in southwest Texas and laboratory analysis of a number of samples have led to an interpretation of origin. Following slight uplift and gulfward tilting of previously deposited marine and terrestrial Cretaceous and Tertiary sediments a peneplane was developed across the beveled edges of these formations, which sloped gently from the Trans-Pecos mountains to the Gulf. Reynosa time began with the uplift of the landward portion of this plain to make the Edwards Plateau on the one side of the Balcones fault and the relative depression of the gulfward side of the fault to make the Rio Grande Plain. After the faulting the rejuvenated streams on the plateau removed the deep residual materials there and cut down into the unweathered calcareous sediments below. The materials thus removed during Reynosa time were transported to and deposited on the surface of the plain as a complex series of fluvial sediments. Continued faulting between the plain and the plateau dragged up the landward portion of the plain, so that the material first deposited at and near the foot of the escarpment was reworked, resulting in a thinning or removal of the formation there and a thickening near the coast.

The uplift of the plateau also stimulated the groundwater circulation and the limestone which is abundant throughout the formation was precipitated as the mechanical sediments were accumulating on the plain, partly at the surface where springs issued and where the water flowed into shallow basins and evaporated and partly in the accumulating gravels and sands where groundwater evaporated.

Read in abstract from manuscript.

Brief remarks were made by Dr. Sidney Powers, with reply by the author.

STRUCTURAL RELATIONS OF THE IGNEOUS ROCKS OF THE WAMSUTTA RED BEDS, MASSACHUSETTS

BY HARRY N. EATON [1]

(Abstract)

The Carboniferous Wamsutta group of Woodworth occupies several detached areas in the Narragansett and Norfolk County basins of Massachusetts and Rhode Island. The type area near North Attleboro covers nearly 15 square miles and lies about 10 miles north of the city of Providence. Superficially the general structure appears to be synclinal but in reality is fan-shaped, pre-

[1] Introduced by T. C. Hopkins and J. B. Woodworth.

Cambrian granite and Lower Cambrian strata being overturned upon Carboniferous. The Wamsutta group comprises clastic red-beds whose deposition must have been local, as separate strata can be traced but short distances. Intercalated among the lower members are (1) large knobs of felsite and (2) smaller masses of basalt. The felsite masses are rather irregular and frequently are associated with felsitic agglomerate. They have been regarded as bosses or dikes intrusive into the sediments. The basalt masses have been described as dikes whose present disrupted condition is due to faulting. Studies begun in 1905 show that the basalt is uniformly vesicular in the upper portions of the masses and is associated with volcanic ash. These masses probably represent two or more nearly contemporaneous surface flows. The history of the acid masses is less definite, but they are probably parts of a flow or flows. The site of the Wamsutta volcanoes is unknown, but Prof. J. B. Woodworth believes that the acid lava came from the northwest and may have had some connection with the intrusive granite-porphyries in Cumberland. Professor Woodward has collaborated in this study.

Presented in abstract extemporaneously.

GEOLOGY AND STRUCTURE OF THE EASTERN HIGHLAND OF CONNECTICUT

BY WILBUR G. FOYE

(*Abstract*)

In cooperation with Dr. H. H. Robinson, Superintendent of the Connecticut Geological Survey, the author has been engaged in the remapping of the Eastern Highland of that State. Results show that the Hebron quartz-biotite schist and the Scotland muscovite schist are the dominant formations of the central part of the area and that they are indistinguishable from Emerson's Paxton and Brimfield schists, respectively, occurring just north in Massachusetts. They are intruded by tonalitic batholiths which are not believed to be younger than Middle Paleozoic in age. The Carboniferous age of these formations is questioned. Schuchert's New Brunswick geanticline borders the geosyncline in which the Hebron and Scotland formations lie on the east.

It is believed that the general structure of the Eastern Highland of Connecticut is that of a horst uplifted in the Jurassic at the time of the foundering of the Appalachian continent to the east and southeast. These events led to the invasion of the Atlantic Ocean into the Long Island Sound embayment.

Read by title in the absence of the author.

GRANITE INTRUSIVE OF THE ROSE DOME, WOODSON COUNTY, KANSAS

BY W. H. TWENHOFEL

(*Abstract*)

The Rose Dome is a structural elevation covering an area of several sections near the southern border of Woodson County, Kansas. Blocks of coarse-grained granite occur over an area of about 100 acres on the north and northwest sides of the apex of the dome. Grading and well-drilling have shown

that the granite blocks on the surface are boulders derived from an intrusive mass of granite, which appears to underlie an area of about 100 acres.

Presented in abstract extemporaneously.

BASIC DIKE INJECTION IN MAGMATIC VEIN SEQUENCES

BY J. E. SPURR

(*Abstract*)

The sequence of magmatic events in connection with ore deposition sometimes shows dikes coming in after veins, although the reverse is the rule, ordinary vein temperature being lower than dike temperature. Dikes also have in some cases injected themselves between the different members of a metallic vein sequence. In probably nine-tenths of the cases where dikes are thus intercalated in the vein sequence, or follow it immediately, the dike is basic—lamprophyric or basaltic. Lamprophyric dikes in other circumstances are often associated with pegmatites, and occur with pegmatites in the aureoles of great igneous intrusions. The lamprophyres are usually later than the pegmatites, and have nevertheless been held to be complementary to them.

The significance of these basic dikes which occur during or immediately after the metallic vein stages is discussed. The metallic vein stages are taken as geothermometers, and the bearing of these cases on the temperature of igneous rocks and of the earth's interior is considered. The conclusions lead to the hypothesis that basic rocks freeze in depth at a lower temperature than siliceous rocks, a temperature about one-half the surface freezing temperature; and that there is no geologic evidence of a regular increment of temperature in the solid crust, as depth is attained.

Read in abstract from manuscript.

Brief remarks were made by Prof. James F. Kemp.

OBSERVATIONS ON DIFFERENT PERIODS OF IGNEOUS ACTIVITY AT BAUXITE, ARKANSAS

BY WILBUR A. NELSON

(*Abstract*)

This paper deals with the possible age of the syenite mass at Bauxite, Arkansas, the character of the bauxite deposits, and the different periods at which bauxite was formed in this district. It is considered that there are three different periods during which bauxite deposits were formed and igneous activity took place.

Read in full from manuscript.

Brief remarks were made by Dr. Hugh D. Miser.

A POSSIBLE FACTOR IN THE FORMATION OF DOLOMITE

BY PERCY E. RAYMOND

(*Abstract*)

That many sedimentary formations commonly called dolomites are associated with disconformities or recurrent diastems seems not to have been stressed. There appear to be two classes of such occurrences. In the first, as exemplified in the Knox, Beekmantown, and many other Cambrian and Lower Ordovician formations, brief emergences were recurrent throughout the period of deposition, as indicated by shrinkage cracks, edgewise conglomerates, etcetera. In the second type, well illustrated by the Galena, and many Richmond and Silurian dolomites, emergence came after the greater part of the formation had been deposited.

So far as is known, dolomite is not being formed in the calcareous oozes beneath sealevel today, which suggsts that its production may be dependent upon somewhat unusual circumstances. Likewise, we have today no opportunity to study the effect of atmospheric waters on recently emerged and unconsolidated calcareous oozes. Theoretically, the different solubilities of magnesium and calcium carbonates should allow unusual opportunities for separation, concentration, recombination, and replacement. Thus, these times of emergence seem critical.

Incidentally, it appears that in stratigraphic work one may generally predict an interruption of the sedimentary record at the end of any period of extensive formation of dolomite.

Read by title in the absence of the author.

ANCIENT TILLITE NEAR GUNNISON, COLORADO

BY WALLACE W. ATWOOD AND WALLACE RICHARDS ATWOOD

(*Abstract*)

In certain bold bluffs just west of Gunnison, and at various localities in the valley of the Gunnison, there are outcrops of a tillite which are certainly of pre-Pleistocene age. The materials in this deposit came almost entirely, if not entirely, from pre-Cambrian formations. The glacial débris rests at places upon pre-Cambrian rocks, and is overlain at places by a volcanic breccia which is presumably of Tertiary age. It is far beyond the maximum position of advance of the Pleistocene glaciers in the region about Gunnison. The formation is in no way associated with the modern ranges of mountains in this vicinity, and it is believed that the ice which deposited this tillite must have formed in mountains of an earlier generation than those of today. At present we favor a correlation of this Gunnison tillite with the Ridgway tillite of Eocene age which was described by the senior author in 1915.

Presented in abstract extemporaneously by the junior author.
Brief remarks were made by Prof. Charles Schuchert.

PRIMARY STRUCTURES OF GRANITE-MASSIVES; THEIR CONTINUATION IN DEPTH, AND THE ECONOMIC CONSEQUENCES

BY ROBERT BALK [1]

(*Abstract*)

Under "primary structures" are included features which have resulted from the fluidal movement of the magma, and features resulting from the earliest stage of fracture. Professor Hans Cloos, of the University of Breslau, under whom the author has studied, has been able to draw conclusions from these primary structures as to the direction of the tectonic pressure during the intrusions, the shape of igneous bodies and their downward continuation; also certain consequences for valuable mineral deposits. Many of the former batholiths in Europe show the presence of an undersurface.

Read in abstract from manuscript.

Brief remarks were made by Professors James F. Kemp and Walter H. Bucher.

MINERALIZATION IN THE PLATTEVILLE-DECORAH CONTACT ZONE OF THE TWIN CITY REGION

BY CLINTON R. STAUFFER

(*Abstract*)

Mineralization has taken place chiefly in the upper part of the Platteville and the basal bed of the Decorah, which constitutes a zone limited above and below by shaly beds. This shows several stages the sequencee of which may be inferred from the relationship of the minerals as they now occur. First solution took place, during which the calcareous shells were removed, leaving open, usually well-preserved, moulds. Dolomitization took place, which was followed by the deposition of pyrite as a coating over the surface of the fossil moulds or filling space in the rock caused by shrinkage due to dolomitization. Finally calcite was deposited in the porous rock and in the pyrite-lined moulds. The finely divided pyrite crusting the top of the upper layer of the Platteville is regarded as an original deposit during a period of non-deposition of sediment—a disconformity.

Read in abstract from manuscript by Prof. F. F. Grout.

ORIGIN OF DESERT DEPRESSIONS

BY CHARLES P. BERKEY AND FREDERICK K. MORRIS

(*Abstract*)

Many deserts contain broad, undrained hollows in which oases are found. Such hollows, seen by our party in the Gobi region, occur within broad structural basins bearing continental sediments of Cretaceous to Quaternary age.

[1] Introduced by J. F. Kemp.

The hollows range from about 300 yards to 30 miles or more in length, and from 50 to 400 feet in depth. Their form varies from rudely elliptical in the smaller hollows to extremely irregular and ramifying in the large ones. They do not follow the pattern of normal river drainage, though the minor details of ground plan at the margins do generally coincide with river pattern. The floors are only thinly covered, so that the bedrock is exposed in many places. Minor hollows are present in the floor and some of these carry small lakes, swamps or saltpans. We are convinced that these hollows never were the basins of large lakes that have since dried up.

We propose the following origin:

1. They begin as true deflation hollows, especially where there is an absence of well-cemented cap rock and the sediments of favorable structure are sandy rather than clayey in composition.

2. The depth of these hollows is limited by a balance between the sheltering of the hollow bottom from the full blast of the wind and the shifting level of groundwater.

3. In times of high groundwater level, vigorous springs or abundant seepages develop in or near the walls of the hollow. These are supported by the enormous bodies of groundwater known to exist in the porous sediments that occupy the Gobi basins, and temporary streams are thus originated which dissect the scarp into a fretwork of stream gullies. The material washed out of the cliff by the streams is mostly fine enough to be carried out of the hollow by wind. In this way the cliff line retreats and the hollow becomes enlarged without the accumulation of much sediment upon the floor of the depression.

Rejuvenation of dissection was observed, due, among other causes, to climatic change.

Undrained hollows were found also in granite, most commonly in coarse-grained granites. In such cases there was surprisingly little waste in these hollows—only a thin cover of arkosic sand and large fragments of weathered granite. The coarse-grained granite breaks down, by disintegration, into grains that the winds can carry and are thus removed, so that the hollow grows. Some of these hollows hold water, which serves then as a check on further deepening. In hard rock and in sedimentary regions alike, the wind serves as a remover of loose débris.

Presented in abstract extemporaneously by the senior author.

ORIGIN OF THE DOLOMITIC LIMESTONE AT ARGENTINE, KANSAS

BY AUSTIN F. ROGERS

(Abstract)

A light gray oolitic limestone of Pennsylvanian age (the Allen limestone) occurring on top of the high bluffs on the south side of the Kansas River at Argentine, Kansas, has been converted in part to a dark gray, dolomitic limestone.

Associated minerals include calcite, barite, sphalerite, chalcopyrite, pyrite, limonite, and kaolinite. The kaolinite occurs in aggregates of minute euhedral

crystals. It has probably been formed from the muscovite of shaly layers in the original limestone.

The dolomitization has been brought about by meteoric waters since the limestone was elevated above the sea.

Presented in abstract extemporaneously.

BEARING OF MARCASITE INCLUSIONS IN FLUORITE ON THE GENESIS OF THE CENTRAL KENTUCKY CALCITE-BARITE-FLUORITE VEINS

BY WM. D. JOHNSTON, JR.[1]

(*Abstract*)

The occurrence of iron sulphides as inclusions in gangue minerals in (*a*) central Kentucky veins, (*b*) western Kentucky veins, and (*c*) Joplin, Missouri, veins is as follows:

(*a*) In the central Kentucky calcite-barite-fluorite veins, marcasite occurs as inclusions in fluorite.

(*b*) In the western Kentucky-southern Illinois fluorite veins, pyrite occurs as inclusions in fluorite

(*c*) At Joplin, Missouri, marcasite occurs as inclusions in calcite.

In all cases, the crystallization of the iron sulphide and the gangue mineral was simultaneous, and the iron sulphide is arranged in zones paralleling certain crystal faces of the gangue mineral. It is believed that the conditions of pressure, temperature, and hydrogen ion concentration at the time of the crystallization of the vein material in central Kentucky were more nearly analogous to the physical and chemical conditions of the Joplin veins than to those of the fluorite veins of western Kentucky and southern Illinois.

Presented in abstract extemporaneously.

SIGNIFICANCE OF THE TACONIC OROGENY

BY CHARLES SCHUCHERT

Read by title.

CONDITIONS OF FORMATION OF THE VARVED GLACIAL CLAY[2]

BY ERNST ANTEVS[3]

(*Abstract*)

The varved late glacial clay was formed in fresh and slightly brackish water in front of the receding ice-border from material brought by glacial rivers. Its chief characteristic is distinct seasonal lamination. This kind of clay, W. A. Johnston found, is now being deposited in the glacial Lake Louise, in the Canadian Rockies. In strongly saline water a massive or almost massive clay was formed, because practically all the clay flocculated and

[1] Introduced by Walter H. Bucher.

[2] Published with the permission of the Director of the Geological Survey of Canada, Ottawa.

[3] Introduced by Jay B. Woodworth.

settled during summer, and in winter no ice-melting worth mentioning occurred. In temperate lakes, as in the postglacial Lake Abitibi, Canada, more or less homogeneous clays are deposited, chiefly because of rapid flocculation in summer and stirring up of the deposits during the inversions of the water stratification in spring and fall, when, because of the uniform density of the water column, storm waves reach the lake bottom.

Water having its greatest density at 39.2° Fahrenheit (+4° centigrade), glacial lakes have permanently their coldest water at the top and their warmest water, of 39.2° Fahrenheit, at the bottom. Thus, the ice-cold melt-water, if discharged at the bottom of the lake, floated up to the surface, bringing along part of the suspended silt and clay. Here it was set in motion in the direction from the ice by the permanent outblowing winds from the high pressure area over the ice-sheet. The transportation in the large, late glacial Lake Timiskaming was remarkable, both with regard to the length of transportation and the quantity of material. In ordinary temperate lakes practically all the fine material floats straight down to the deepest part of the lake basin.

The relatively coarse material was deposited during the melting season, while the finest particles settled first during the winter, as is evident from the upward increasing fineness of the annual deposit and the extremely fine texture of the topmost part. The cause of this, and thus also of the distinct lamination, was slow flocculation in summer time of the finest clay. The conditions of the slow coagulation are at least partly known. Thus it may have been of great importance that the material, as coming from glaciers, partly consisted of freshly ground rock, of clay that had not previously been flocculated and deposited. Other important factors were the high density and viscosity of the ice-cold lake water. Still other important conditions were the unchanged stratification of the water of the lakes and the permanent thermocline, or discontinuity layer, the zone of rapid temperature change, usually at a depth of 8 to 25 meters, and the lower limit of surface circulation, which prevented storms from stirring up the lower water strata and material that had settled.

Read by title.

MORAINES OF RECESSION BETWEEN INDIANA AND NEW ENGLAND

BY FRANK B. TAYLOR

(*Abstract*)

This paper relates chiefly to features shown on a map which accompanies it. So far as known to the writer, the map shows all of the recessional moraines of the last, or Wisconsin, ice-sheet between Indiana and New England—all, at least, which have been mapped with sufficient care, and over distances great enough to show their relations to the other members of the series. For the present, the group of moraines in western New England stands apart, but they will no doubt be connected at no distant date with those farther west and north.

The front of the Wisconsin recessional moraine series is represented on this map by the Hartwell moraine, which, according to Leverett, passes about

ten miles north of Cincinnati. Taking this moraine as number 1, and counting the series northward and northeastward in the axes of the Miami and Maumee valleys to Toledo, and thence along the south side of Lake Erie and northeastward through western and northern New York to the Canadian boundary north of Plattsburg, 32 moraines are numbered in consecutive series. Four more on the upper Ottawa River, found by the writer in 1895, probably belong to the same series. Two unexplored intervals, one between northern New York and the moraines on the upper Ottawa and another from the northern edge of the map to the Height of Land south of Lake Abitibi, will probably yield four or five moraines each, say ten additional moraines, making 46 in all.

These moraines constitute one of the most perfect examples of periodicity and rhythm which have been found in geological formations. It seems certain that if the influence of topography in causing irregularities in the intermorainic space intervals could be eliminated, the series—at least that part which lies west of the Champlain-Hudson depression—would be seen to be equally spaced throughout and corresponding, of course, to an equally regular periodic oscillation in the general climatic amelioration.

The bearing of this series of moraines on the general nature of the cause of glaciation seems clear, for no purely terrestrial cause, like a diversion of the Gulf Stream or uplifts and subsidences of the land, can be supposed to produce rhythmic forms in such perfection. It is hard to think of any but an astronomical cause which could produce such a result.

Leverett formerly recognized two divisions of the Wisconsin drift, early and late, based mainly on discordances of the moraine systems; but subsequently a third division was recognized. This is marked by the Port Huron morainic system in Michigan and Ontario, and the Alden moraine, a few miles south of Buffalo, in western New York, is definitely identified as the latest member of that system. Thus what was formerly called Late Wisconsin is now in part called Middle Wisconsin, and the front of the Late Wisconsin is placed at the Port Huron morainic system. Each of these discordances marks a more pronounced episode of retreat and readvance than the average and tends to lengthen the time factor over that indicated by the moraine series alone. But this effect is probably not great.

Read by title.

GEOLOGY OF THE ISLAND OF MAUI, HAWAII

BY NORMAN E. A. HINDS[1]

(*Abstract*)

The island of Maui, the second largest of the Hawaiian group, is the principal section of a great volcanic structure which includes, in addition, the islands of Molokai (with the slightly submerged Penguin Bank, extending westward from west Molokai toward Oahu), Lanai, and Kahoolawe. Whether these islands were ever joined above sealevel is uncertain, but their close submarine connection is clearly shown by the hydrographic charts of the islands. The Maui group (Maui-Molokai-Lanai-Kahoolawe) is separated from Hawaii

[1] Introduced by John P. Buwalda.

by a channel 32 miles in width and from 6,000 to 10,000 feet in depth; the channel between the Penguin Bank and Oahu is about 12 miles in width and from 2,000 to 2,300 feet in depth. The submarine connection between the Maui group and Oahu, therefore, is much closer than that with Hawaii. It is not improbable that Oahu and the Maui group form a huge, complex, lava dome; Hawaii, with its various members, is a distinct volcanic unit.

The island of Maui is composed of two domes, connected by a low saddle not more than 250 feet in elevation. Haleakala, east Maui (elevation 10,032 feet), is a young dome, with its constructional surface and its many parasitic cinder cones for the most part well preserved. On the northern, northeastern, and southeastern slopes the heavy trade wind rainfall has given rise to numerous streams which have cut deep, young canyons into the flanks of the dome, thereby exposing limited sections of its underground structure. Broad, tabular, practically undissected interfluves separate the gorges. The heads of most of the canyons are a considerable distance below the summit of Haleakala, which projects well above the zone of maximum rainfall. The upper portion of the windward slopes and all of the leeward slopes are virtually untouched by erosion. The cinder cones vary in age, and consequently in their stage of dissection. The oldest cones on the windward (northern and northeastern) slopes have been most deeply eroded. The windward coast of the dome has been wave-cliffed to some extent; the leeward coast shows little cliffing.

At the summit of Haleakala is a great faulted depression, 7.8 miles in length and 2.3 miles in width; the walls are steeply sloping scarps 2,000 to 2,500 feet in height. Two fault-gaps, one on the northern and one on the eastern side, break the continuity of the walls. On the floor of the depression are a number of very recent cinder cones and lava-flows. The walls of the depression are practically untouched by erosion, except to a limited extent on the eastern side, where the heaviest rains fall. The depression has been explained, both as a volcanic rent and as a volcanic sink. Insufficient field-work has been done to determine the exact nature of the dislocation.

From the geomorphologic evidence, Haleakala appears to be slightly older than Mauna Kea, Hawaii, whose erosional features closely duplicate those of the former dome. The principal eruptive center of Haleakala probably became extinct late in the Glacial period; eruptions from subsidiary fissures continued into the historic period, and much later than on Mauna Kea.

West Maui (elevation, 5,788 feet) is a much smaller and older dome, which has been greatly dissected by many streams radiating from a slightly dissected summit plateau, the center of the heaviest rainfall and the principal watershed. The fluviatile topography of the dome is submature, but the heavier rainfall over the windward slopes has caused more rapid erosion, and hence a somewhat more advanced topographic development of that section of the dome. Since the headward growth of the canyons has not been completed, the small remnant of the original constructional surface forming the summit plateau has been preserved. Stupendous sea-cliffs have been cut into the northern and northeastern coasts; low cliffs are also present locally along the leeward coast. Judging from the extent of fluviatile and marine abrasion, the principal eruptive center of west Maui became extinct during the late Tertiary. The completion of the west Maui and the Kauai domes probably took place approximately at the same time.

Read by title.

USE OF THE TERM "SINIAN"

BY A. W. GRABAU

(*Abstract*)

The use of the term "Sinian" is advocated for those pre-Cambrian deposits which are but little altered. These deposits are extensively developed in China and are particularly characteristic of that region. Von Richthofen recognized the beds and named them Sinian without correlating them more definitely than to consider them earlier than what he thought Carboniferous limestones, which are now known to be Ordovician in age. This places the vast accumulation of Sinian beds in the Cambrian or earlier. The Cambrian of China is represented by the upper portion of von Richthofen's Sinian series and it is principally marine. Most of his Sinian is now known to be pre-Cambrian and continental, with enough characteristic fossils to identify it in most localities.

Grabau therefore proposes that von Richthofen's pre-Cambrian Sinian, which is of systemic magnitude and importance, shall be termed the "Sinian System." This system may be placed either at the top of the Proterozoic, although it is no more metamorphosed than the immediately succeeding Cambrian rock, or placed, as pre-Cambrian Paleozoic, at the present known base of the Paleozoic. The latter view is held by Grabau and other investigators on the Chinese Geological Survey.

Read by title.

ADDRESS OF THE RETIRING PRESIDENT OF THE MINERALOGICAL SOCIETY OF AMERICA

At 12.15 the Society went into joint session with the Mineralogical Society to listen to the address of the retiring President of that Society, Henry S. Washington. Title: "The modern study of minerals." This address is printed in full in The American Mineralogist.

At the close of the address of Doctor Washington, Professor Kemp presented the following resolution for consideration by the Society:

RESOLUTION OF THANKS

Resolved, That the Geological Society of America express its deeply felt thanks to the President and Trustees of Cornell University, and to the chairman and members of the local committee, for the hospitalities enjoyed by the Society during the thirty-seventh annual meeting. Every facility and courtesy have been freely placed at the service of the fellowship and have reacted in making possible an exceptionally instructive and enjoyable meeting.

In returning its thanks, the Society is peculiarly sensible of the welcome given it because it has been celebrating the thirty-seventh anniver-

sary of its original organization, at Cornell University, in December, 1888.

JAMES F. KEMP.
I. C. WHITE.

Chairman Schuchert then announced that the business, the scientific sessions, and other activities of the annual meeting of 1924 had been completed, and, on motion, the thirty-seventh annual meeting adjourned at 1 o'clock.

CHARLES P. BERKEY,
Secretary.

Register of the Ithaca Meeting, 1924

FELLOWS

Cleveland Abbe, Jr.
Harold L. Alling
George H. Ashley
J. Austen Bancroft
Florence Bascom
R. S. Bassler
Alan M. Bateman
Clyde Max Bauer
Charles P. Berkey
Edward W. Berry
Eliot Blackwelder
J. A. Bownocker
E. B. Branson
T. M. Broderick
Walter H. Bucher
Lancaster D. Burling
Bert S. Butler
J. Ernest Carman
Charles Camsell
T. C. Chamberlin
Bruce L. Clark
H. F. Cleland
John M. Clarke
A. P. Coleman
A. R. Crook
Nelson C. Dale
E. De Golyer
Arthur S. Eakle
C. N. Fenner
August F. Foerste
Ferdinand Julius Fohs
Albert W. Giles
Clarence E. Gordon
U. S. Grant
Louis C. Graton
Frank F. Grout
Gilbert D. Harris
Chris A. Hartnagel
K. C. Heald
Thomas C. Hopkins
W. O. Hotchkiss
Walter F. Hunt
E. C. Jacobs
Douglas Johnson
James F. Kemp
Adolph Knopf
Edward H. Kraus
Henry B. Kummel
Andrew C. Lawson
Waldemar Lindgren
Homer P. Little
Chester R. Longwell
Frederick B. Loomis
Gerald F. Loughlin
George C. Martin
Kirtley F. Mather
Edward B. Mathews
W. D. Matthew
B. R. MacKay
Maurice G. Mehl
Benjamin L. Miller
Hugh D. Miser
Wilbur A. Nelson
William A. Parks
R. A. F. Penrose, Jr.
Alexander H. Phillips
Sidney Powers
Chester A. Reeds
John B. Reeside, Jr.
Wm. North Rice
Heinrich Ries
Austin F. Rogers
Rudolf Ruedemann
W. T. Schaller

CHARLES SCHUCHERT
WILLIAM J. SINCLAIR
JOSEPH T. SINGEWALD, JR.
GEORGE OTIS SMITH
R. E. SOMERS
J. E. SPURR
MIGNON TALBOT
FRANK B. TAYLOR
JOHN L. TILTON
ARTHUR C. TROWBRIDGE
EDWARD L. TROXELL
W. H. TWENHOFEL
FRANK R. VAN HORN
HENRY S. WASHINGTON
WALTER H. WEED
STUART WELLER
CHESTER K. WENTWORTH
LEWIS G. WESTGATE
DAVID WHITE
I. C. WHITE
MORLEY EVANS WILSON
ALEXANDER N. WINCHELL
FRED. E. WRIGHT

FELLOWS-ELECT

R. J. COLONY
CHARLES R. FETTKE
THOMAS MCDOUGALL HILLS
EDWARD SAMPSON
EDMUND MAUTE SPIEKER

In addition to the foregoing, there were registered at the meeting 112 members of affiliated societies and visitors.

Lists of Former Officers and Meetings, with Dates

By recommendation of the Council, a complete list of past officers, with the dates of their service, is printed in the Proceedings.

PRESIDENTS

1889.	James Hall	1907.	C. R. Van Hise
1890.	James D. Dana	1908.	Samuel Calvin
1891.	Alexander Winchell	1909.	Grove K. Gilbert
1892.	G. K. Gilbert	1910.	Arnold Hague
1893.	J. William Dawson	1911.	William M. Davis
1894.	T. C. Chamberlin	1912.	H. L. Fairchild
1895.	N. S. Shaler	1913.	Eugene A. Smith
1896.	Joseph Le Conte	1914.	George F. Becker
1897.	Edward Orton	1915.	Arthur P. Coleman
1898.	J. J. Stevenson	1916.	John M. Clarke
1899.	B. K. Emerson	1917.	Frank D. Adams
1900.	G. M. Dawson	1918.	Whitman Cross
1901.	C. D. Walcott	1919.	J. C. Merriam
1902.	N. H. Winchell	1920.	I. C. White
1903.	S. F. Emmons	1921.	James F. Kemp
1904.	J. C. Branner	1922.	Charles Schuchert
1905.	Raphael Pumpelly	1923.	David White
1906.	I. C. Russell	1924.	Waldemar Lindgren

VICE-PRESIDENTS

(*Not including ex-officio Vice-Presidents representing the affiliated Societies*)

1889.	James D. Dana	Alexander Winchell
1890.	J. S. Newberry	A. Winchell
1891.	G. K. Gilbert	T. C. Chamberlin
1892.	J. W. Dawson	T. C. Chamberlin
1893.	T. C. Chamberlin	J. J. Stevenson
1894.	N. S. Shaler	G. H. Williams
1895.	Joseph Le Conte	Charles H. Hitchcock
1896.	Charles H. Hitchcock	Edward Orton
1897.	J. J. Stevenson	B. K. Emerson
1898.	B. K. Emerson	G. M. Dawson
1899.	G. M. Dawson	C. D. Walcott
1900.	C. D. Walcott	N. H. Winchell
1901.	N. H. Winchell	S. F. Emmons
1902.	S. F. Emmons	J. C. Branner
1903.	Arnold Hague	H. S. Williams
1904.	H. S. Williams	Samuel Calvin
1905.	Samuel Calvin	W. M. Davis
1906.	W. M. Davis	E. A. Smith
1907.	J. S. Diller	A. P. Coleman
1908.	George F. Becker	A. C. Lawson
1909.	Frank D. Adams	John M. Clarke

1910.	CHARLES SCHUCHERT	A. P. LOW
1911.	WILLIAM NORTH RICE	
1912.	ISRAEL C. WHITE	
1913.	JAMES F. KEMP	R. D. SALISBURY
1914.	WALDEMAR LINDGREN	HORACE B. PATTON
1915.	L. V. PIRSSON	H. P. CUSHING
1916.	J. P. IDDINGS	H. F. REID
1917.	A. C. LAWSON	W. D. MATTHEW
1918.	BAILEY WILLIS	FRANK LEVERETT
1919.	R. A. F. PENROSE, JR.	HERBERT E. GREGORY
1920.	GEORGE P. MERRILL	W. G. MILLER
1921.	J. B. WOODWORTH	ARTHUR KEITH
1922.	HERNY S. WASHINGTON	ROBERT T. HILL
1923.	W. H. HOBBS	W. H. EMMONS
1924.	WILLIAM A. PARKS	JOHAN A. UDDEN

TREASURERS

1889–1891.	H. S. WILLIAMS
1892–1906.	I. C. WHITE
1907–1917.	W. B. CLARK
1917–	E. B. MATHEWS

SECRETARIES

1889–1890.	JOHN J. STEVENSON
1891–1906.	H. L. FAIRCHILD
1907–1922.	E. O. HOVEY
1923–	CHARLES P. BERKEY

EDITORS

1890–1892.	W J McGEE
1893–	J. STANLEY-BROWN

COUNCILORS

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1890.	J. W. POWELL	G. M. DAWSON	C. H. HITCHCOCK
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1892.	N. H. WINCHELL	H. S. WILLIAMS	
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1897.	J. S. DILLER	W. B. SCOTT	
1898.	ROBERT BELL	M. E. WADSWORTH	
1899.	W. M. DAVIS	JOSEPH A. HOLMES	
1900.	W. B. CLARK	A. C. LAWSON	
1901.	SAMUEL CALVIN	ARTHUR P. COLEMAN	
1902.	C. W. HAYES	J. P. IDDINGS	
1903.	R. D. SALISBURY	J. E. WOLFF	
1904.	JOHN M. CLARKE	GEORGE P. MERRILL	
1905.	H. M. AMI	J. F. KEMP	
1906.	A. C. LANE	DAVID WHITE	
1907.	H. E. GREGORY	H. F. REID	
1908.	H. P. CUSHING	H. B. PATTON	
1909.	G. O. SMITH	H. S. WASHINGTON	

1910.	J. B. Woodworth	C. S. Prosser
1911.	A. H. Purdue	Heinrich Ries
1912.	S. W. Beyer	Arthur Keith
1913.	Whitman Cross	W. G. Miller
1914.	R. A. F. Penrose, Jr.	W. W. Atwood
1915.	Charles K. Leith	Thomas L. Watson
1916.	Frank B. Taylor	Charles P. Berkey
1917.	Arthur L. Day	William H. Emmons
1918.	Joseph Barrell	R. A. Daly
1919.	William S. Bayley	Eugene W. Shaw
1920.	T. W. Vaughan	George F. Kay
1921.	L. C. Graton	G. D. Louderback
1922.	E. S. Bastin	L. G. Westgate
1923.	E. O. Hovey	A. H. Brooks
	Charles Camsell	J. A. Bownocker
1924.	Fred. E. Wright	William H. Twenhofel

ANNUAL AND SEMI-ANNUAL MEETING PLACES

1888. Ithaca, New York.
1889. Toronto, Canada, August.
New York City, December.
1890. Indianapolis, Indiana, August.
Washington, D. C., December.
1891. Washington, D. C., August.
Columbus, Ohio, December.
1892. Rochester, New York, August.
Ottawa, Canada, December.
1893. Madison, Wisconsin, August.
Boston, Massachusetts, December.
1894. Brooklyn, New York, August.
Baltimore, Maryland, December.
1895. Springfield, Massachusetts, August.
Philadelphia, Pennsylvania, December.
1896. Buffalo, New York, August.
Washington, D. C., December.
1897. Detroit, Michigan, August.
Montreal, Canada, December.
1898. Boston, Massachusetts, August.
New York City, December.
1899. Columbus, Ohio, August.
Washington, D. C., December.
1900. New York City, June.
Albany, New York, December.
1901. Denver, Colorado, August.
Rochester, New York, December.
1902. Pittsburgh, Pennsylvania, July.
Washington, D. C., December.
1903. Saint Louis, Missouri, December.
1904. Philadelphia, Pennsylvania, December.

1905. Ottawa, Canada, December.
1906. New York City, December.
1907. Albuquerque, New Mexico, December.
1908. Baltimore, Maryland, December.
1909. Cambridge and Boston, Massachusetts, December.
1910. Pittsburgh, Pennsylvania, December.
1911. Washington, D. C., December.
1912. New Haven, Connecticut, December.
1913. Princeton, New Jersey, December.
1914. Philadelphia, Pennsylvania, December.
1915. Leland-Stanford, Jr., University, California, August.
Washington, D. C., December.
1916. Albany, New York, December.
1917. Saint Louis, Missouri, December.
1918. Baltimore, Maryland, December.
1919. Boston, Massachusetts, December.
1920. Chicago, Illinois, December.
1921. Amherst, Massachusetts, December.
1922. Ann Arbor, Michigan, December.
1923. Washington, D. C., December.
1924. Ithaca, New York, December.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS FOR 1925

President:

WILLIAM B. SCOTT, Princeton, N. J.

Vice-Presidents:

REGINALD W. BROCK, Vancouver, B. C.
MARIUS R. CAMPBELL, Washington, D. C.
R. S. LULL, New Haven, Conn.
ARTHUR S. EAKLE, Berkeley, Calif.

Secretary:

CHARLES P. BERKEY, Columbia University, New York, N. Y.

Secretary pro Tem:

JAMES F. KEMP, Columbia University, New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1925)

CHARLES CAMSELL, Ottawa, Canada
J. A. BOWNOCKER, Columbus, Ohio

(Term expires 1926)

FRED. E. WRIGHT, Washington, D. C.
WILLIAM H. TWENHOFEL, Madison, Wis.

(Term expires 1927)

U. S. GRANT, Evanston, Ill.
FLORENCE BASCOM, Bryn Mawr, Pa.

MEMBERSHIP, 1925

CORRESPONDENTS

BARROIS, CHARLES, Lille, France. Dec., 1909.
BRÖGGER, W. C., Christiania, Norway. Dec., 1909.
DAVID, SIR TANNATT WILLIAM EDGEWORTH, Sydney, New South Wales. Dec., 1923.
DE GEER, BARON GERHARD, Stockholm, Sweden. Dec., 1910.
DE MARGERIE, EMMANUEL, Strassburg, Alsace, France. Dec., 1921.
HARKER, ALFRED, Cambridge, England. Dec., 1924.
HEIM, ALBERT, Zurich, Switzerland. Dec., 1909.
KAYSER, EMANUEL, Marburg, Germany. Dec., 1909.
KILIAN, W., Grenoble, France. Dec., 1912.
KOTO, BUNJIRO, Tokyo, Japan. Dec., 1923.
LACROIX, FRANÇOIS ANTOINE ALFRED, Paris, France. Dec., 1923.
MOLENGRAAFF, GUSTAAF ADOLF FREDERIK, Delft, Holland. Dec., 1923.
ROGERS, ARTHUR WILLIAM, Cape Town, South Africa. Dec., 1924.
SEDERHOLM, JAKOB JOHANNES, Helsingfors, Finland. Dec., 1923.
WOODWARD, ARTHUR SMITH, London, England. Dec., 1923.

FELLOWS

* Indicates Original Fellows (see article III of Constitution)

ABBE, CLEVELAND, JR., College of the City of New York, New York, N. Y. August, 1899.
ADAMS, FRANK DAWSON, McGill University, Montreal, Canada. Dec., 1889.
ADAMS, GEORGE I., University of Alabama, Tuscaloosa, Ala. Dec., 1902.
ADAMS, LEASON H., Geophysical Laboratory, Washington, D. C. Dec., 1922.
ADKINS, WALTER S., Apartado 150, Tampico, Tamaulipas, Mexico. Dec., 1921.
ALCOCK, F. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
ALDEN, WILLIAM C., U. S. Geological Survey, Washington, D. C. Dec., 1909.
ALDRICH, TRUMAN H., 1026 Glen Iris Ave., Birmingham, Ala. May, 1889.
ALLAN, JOHN A., University of Alberta, Edmonton, Alberta, Canada. Dec., 1914.
ALLEN, EUGENE T., Geophysical Laboratory, Washington, D. C. Dec., 1922.
ALLEN, R. C, 1202 Hanna Bldg., Cleveland, Ohio. Dec., 1911.
ALLING, H. L., University of Rochester, Rochester, N. Y. Dec., 1920.
AMI, HENRY M., Victoria Museum, Room 105, Ottawa, Canada. Dec., 1889.
ANDERSON, FRANK M., State Mining Bureau, 2604 Ætna St., Berkeley, Calif. Dec., 1902.
ANDERSON, ROBERT V., Menlo Park, Calif. Dec., 1911.
ANDREWS, E. C., Geol. Surv. of N. S. W., Sydney, N. S. Wales. Dec., 1920.
ARNOLD, RALPH, 639 South Spring St., Los Angeles, Calif. Dec., 1904.
ASHLEY, GEORGE HALL, State Capitol, Harrisburg, Pa. August, 1895.
ATWOOD, WALLACE WALTER, Clark University, Worcester, Mass. Dec., 1909.
BAGG, RUFUS MATHER, JR., 7 Brokaw Place, Appleton, Wis. Dec., 1896.
BAIN, H. FOSTER, 1430 33d St. N. W., Washington, D. C. Dec., 1895.
BAKER, MANLEY BENSON, School of Mining, Kingston, Ontario. Dec., 1911.

BALDWIN, S. PRENTISS, 11025 East Blvd., Cleveland, Ohio. August, 1895.
BALL, MAX WAITE, 1104 First Natl. Bank Bldg., Denver, Colo. Dec., 1924.
BALL, SYDNEY H., 42 Broadway, New York City. Dec., 1905.
BANCROFT, JOSEPH A., McGill University, Montreal, Canada. Dec., 1914.
BARBOUR, ERWIN HINCKLEY, University of Nebraska, Lincoln, Neb. Dec., 1896.
BARRETT, LESLIE PARK, Geol. Surv. of Michigan, Lansing, Mich. Dec., 1923.
BARTON, DONALD C., Amerada Petr. Corp., Houston, Texas. Dec., 1921.
BARTON, GEORGE H., Boston Soc. of Nat. History, Boston, Mass. Aug., 1890.
BARTSCH, PAUL, U. S. National Museum, Washington, D. C. Dec., 1917.
BASCOM, FLORENCE, Bryn Mawr College, Bryn Mawr, Pa. August, 1894.
BASSLER, RAY SMITH, U. S. National Museum, Washington, D. C. Dec., 1906.
BASTIN, EDSON S., University of Chicago, Chicago, Ill. Dec., 1909.
BATEMAN, ALAN MARA, Yale University, New Haven, Conn. Dec., 1916.
BAUER, CLYDE MAX, 114 Yellowstone Ave., Billings, Mont. Dec., 1923.
BAYLEY, WILLIAM S., University of Illinois, Urbana, Ill. Dec., 1888.
BEEDE, JOSHUA W., 225 Diaz St., San Antonio, Texas. Dec., 1902.
BELL, WALTER A., Victoria Memorial Museum, Ottawa, Canada. Dec., 1923.
BENSON, W. N., University of Otago, Dunedin, New Zealand. Dec., 1919.
BERKEY, CHARLES P., Columbia University, New York, N. Y. August, 1901.
BERRY, EDWARD WILBER, Johns Hopkins University, Baltimore, Md. Dec., 1909.
BEYER, SAMUEL WALKER, Iowa Agricultural College, Ames, Iowa. Dec., 1896.
BILLINGSLEY, PAUL, 605 Pioneer Bldg., Seattle, Wash. Dec., 1922.
BLACKWELDER, ELIOT, Leland Stanford Jr. University, Stanford University, Calif. Dec., 1908.
BOUTWELL, JOHN M., Natl. Copper Bank, Salt Lake City, Utah. Dec., 1905.
BOWEN, CHARLES F., c/o Standard Oil Co., 26 Broadway, New York City. Dec., 1916.
BOWEN, N. L., Geophysical Laboratory, Washington, D. C. Dec., 1917.
BOWIE, WILLIAM, U. S. Coast and Geodetic Survey, Washington, D. C. Dec., 1919.
BOWMAN, ISAIAH, American Geographical Society, Broadway at 156th St., New York City. Dec., 1924.
BOWNOCKER, JOHN ADAMS, Ohio State University, Columbus, Ohio. Dec., 1904.
BRANSON, EDWIN BAYER, University of Missouri, Columbia, Mo. Dec., 1911.
BRETZ, J HARLEN, University of Chicago, Chicago, Ill. Dec., 1917.
BRIGHAM, ALBERT PERRY, Colgate University, Hamilton, N. Y. Dec., 1893.
BROCK, REGINALD W., Univ. of British Columbia, Vancouver, B. C. Dec., 1904.
BRODERICK, T. MONTEITH, Calumet and Hecla Mining Co., Calumet, Mich. Dec., 1921.
BROKAW, A. D., 157 Maplewood Ave., Maplewood, N. J. Dec., 1920.
BROWN, BARNUM, American Museum of Natural History, New York, N. Y. Dec., 1910.
BROWN, CHARLES WILSON, Brown University, Providence, R. I. Dec., 1908.
BROWN, JOHN STAFFORD, Dept. Geology, Columbia University, New York City. Dec., 1922.
BROWN, THOMAS CLACHAR, Laurel Bank Farm, Fitchburg, Mass. Dec., 1915.
BRUCE, E. L., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
BRYAN, KIRK, U. S. Geological Survey, Washington, D. C. Dec., 1922.
BUCHER, W. H., University of Cincinnati, Cincinnati, Ohio. Dec., 1920.

BUDDINGTON, A. F., 124 Pyne Hall, Princeton, N. J. Dec., 1919.
BUEHLER, HENRY ANDREW, Rolla, Mo. Dec., 1909.
BURCHARD, E. F., U. S. Geological Survey, Washington, D. C. Dec., 1920.
BURLING, LANCASTER D., Vassar College, Poughkeepsie, N. Y. Dec., 1917.
BURWASH, EDWARD M. J., University of British Columbia, Vancouver, B. C. Dec., 1916.
BUTLER, BERT S., Box 277, Calumet, Mich. Dec., 1912.
BUTLER, G. MONTAGUE, College of Mines, Tucson, Arizona. Dec., 1911.
BUTTS, CHARLES, U. S. Geological Survey, Washington, D. C. Dec., 1912.
BUWALDA, J. P., University of California, Berkeley, Calif. Dec., 1920.
CADY, G. H., Fayetteville, Ark. Dec., 1920.
CALHOUN, FRED HARVEY HALL, Clemson College, S. C. Dec., 1909.
CALKINS, FRANK C., U. S. Geological Survey, Washington, D. C. Dec., 1914.
CAMPBELL, HENRY D., Washington and Lee Univ., Lexington, Va. May, 1889.
CAMPBELL, MARIUS R., U. S. Geological Survey, Washington, D. C. Aug., 1892.
CAMSELL, CHARLES, Department of Mines, Ottawa, Canada. Dec., 1914.
CAPPS, STEPHEN R., JR., U. S. Geological Surv., Washington, D. C. Dec., 1911.
CARMAN, J. ERNEST, Ohio State University, Columbus, Ohio. Dec., 1917.
CARNEY, FRANK, Box 309, Eldorado, Kans. Dec., 1908.
CASE, ERMINE C., University of Michigan, Ann Arbor, Mich. Dec., 1901.
CHADWICK, GEORGE H., 305 Maverick Bldg., San Antonio, Texas. Dec., 1911.
CHAMBERLIN, ROLLIN T., University of Chicago, Chicago, Ill. Dec., 1913.
*CHAMBERLIN, T. C., Hyde Park Hotel, Hyde Park Blvd. and Harper Ave., Chicago, Ill.
CLAPP, CHARLES H., State University, Missoula, Mont. Dec., 1914.
CLAPP, FREDERICK G., 30 Church St., New York City. Dec., 1905.
CLARK, BRUCE L., Bacon Hall, Univ. of California, Berkeley, Calif. Dec., 1918.
CLARK, F. R., 723 Petroleum Bldg., Tulsa, Okla. Dec., 1919.
CLARK, W. O., Pahala, Kau, Hawaii. Dec., 1920.
CLARKE, EDWARD DE COURCY, University of Western Australia, Perth, Western Australia. Dec., 1924.
CLARKE, JOHN MASON, Education Bldg., Albany, N. Y. Dec., 1897.
CLELAND, HERDMAN F., Williams College, Williamstown, Mass. Dec., 1905.
CLEMENTS, J. MORGAN, 20 Broad St., New York City. Dec., 1894.
COBB, COLLIER, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
COLEMAN, ARTHUR P., Toronto University, Toronto, Canada. Dec., 1896.
COLLIER, ARTHUR J., U. S. Geological Survey, Washington, D. C. June, 1902.
COLLINS, WILLIAM H., Geological Survey, Ottawa, Canada. Dec., 1921.
COLONY, ROY JED, Columbia University, New York City. Dec., 1924.
CONDIT, D. DALE, c/o Carr Bros., 65 Broadway, New York City. Dec., 1916.
COOK, CHARLES W., University of Michigan, Ann Arbor, Mich. Dec., 1915.
COOKE, C. WYTHE, U. S. Geological Survey, Washington, D. C. Dec., 1918.
COSTE, EUGENE, 410 Royal Bank Bldg., Toronto, Canada. Dec., 1906.
COTTON, LEO ARTHUR, University of Sydney, Sydney, Australia. Dec., 1924.
CRAWFORD, RALPH DIXON, 1050 Tenth St., Boulder, Colo. Dec., 1916.
CROOK, ALJA R., State Museum of Natural History, Springfield, Ill. Dec., 1898.
*CROSBY, WILLIAM O., Massachusetts Institute of Technology, Boston, Mass.
CROSS, WHITMAN, 101 East Kirke St., Chevy Chase, Md. May, 1889.
CULVER, GARRY E., 310 Center Ave., Stevens Point, Wis. Dec., 1891.

CUMINGS, EDGAR R., Indiana University, Bloomington, Ind. August, 1901.
CUSHMAN, J. A., Sharon, Mass. Dec., 1919.
DAKE, C. L., Missouri School of Mines, Rolla, Mo. Dec., 1920.
DALE, N. C., Hamilton College, Clinton, N. Y. Dec., 1920.
DALY, REGINALD A., Harvard University, Cambridge, Mass. Dec., 1905.
DANA, EDWARD SALISBURY, Yale University, New Haven, Conn. Dec., 1908.
*DARTON, NELSON H., U. S. Geological Survey, Washington, D. C.
DAVIS, E. F., 417 E. Randolph St., Glendale, Calif. Dec., 1920.
*DAVIS, WILLIAM M., 31 Hawthorne St., Cambridge, Mass.
DAY, ARTHUR LOUIS, Geophysical Laboratory, Washington, D. C. Dec., 1909.
DAY, DAVID T., 1333 F St. N. W., Washington, D. C. August, 1891.
DEAN, BASHFORD, Riverdale-on-Hudson, New York, N. Y. Dec., 1910.
DECKER, CHARLES ELIJAH, University of Oklahoma, Norman, Okla. Dec., 1924.
DE GOLYER, E. L., 65 Broadway, New York City. Dec., 1918.
DEUSSEN, ALEXANDER. 504 Stewart Bldg., Houston, Texas. Dec., 1916.
DE WOLF, FRANK WILBRIDGE, Humphreys Oil Co., Great Southern Life Bldg., Dallas, Texas. Dec., 1909.
DICKERSON, ROY E., c/o G. C. Gester, 225 Bush St., San Francisco, Cal. Dec., 1918.
*DILLER, JOSEPH S., U. S. Geological Survey, Washington, D. C.
D'INVILLIERS, EDWARD V., 121 North Broad St., Philadelphia, Pa. Dec., 1888.
DODGE, RICHARD E., Storrs, Conn. August, 1897.
DOLMAGE, VICTOR, 510 Pacific Bldg., Vancouver, B. C. Dec., 1922.
DRAKE, NOAH FIELDS, Fayetteville, Ark. Dec., 1898.
DRESSER, JOHN A., 701 Eastern Townships Bank Bldg., Montreal, Canada. Dec., 1906.
*DUMBLE, EDWIN T., 316 Pacific Bldg., Houston, Texas.
DUNBAR, C. O., Yale University, New Haven, Conn. Dec., 1920.
EAKLE, ARTHUR S., University of California, Berkeley, Calif. Dec., 1899.
ECKEL, EDWIN C., 1503 Decatur St. N. W., Washington, D. C. Dec., 1905.
EMERY, WILSON B., Casper, Wyoming. Dec., 1919.
*EMERSON, BENJAMIN K., Amherst, Mass.
EMMONS, WILLIAM H., Univ. of Minnesota, Minneapolis, Minn. Dec., 1912.
*FAIRCHILD, HERMAN L., University of Rochester, Rochester, N. Y.
FARRINGTON, OLIVER C., Field Museum of Natural History, Chicago, Ill. Dec., 1895.
FATH, A. E., Vacuum Oil Co., 61 Broadway, New York, N. Y. Dec., 1920.
FENNEMAN, NEVIN M., University of Cincinnati, Cincinnati, Ohio. Dec., 1904.
FENNER, CLARENCE N., Geophysical Laboratory, Washington, D. C. Dec., 1911.
FERGUSON, H. G., U. S. Geological Survey, Washington, D. C. Dec., 1920.
FETTKE, CHARLES R., Carnegie Institute of Technology, Pittsburgh, Pa. Dec., 1924.
FISHER, CASSIUS ASA, 711 First Nat'l Bank Bldg., Denver, Colo. Dec., 1908.
FOERSTE, AUGUST F., 129 Wroe Ave., Dayton, Ohio. Dec., 1899.
FOHS, FERDINAND JULIUS, 60 Broadway, New York, N. Y. Dec., 1923.
FORD, WILLIAM E., Sheffield Scientific School, New Haven, Conn. Dec., 1915.
FOYE, W. G., Wesleyan University, Middletown, Conn. Dec., 1919.
FULLER, MYRON L., 60 Main St., Brockton, Mass. Dec., 1898.
GALLOWAY, J. J., Columbia University, New York, N. Y. Dec., 1920.

GALPIN, SIDNEY L., 630 Park Ave., Ames, Iowa. Dec., 1917.
GANE, HENRY STEWART, Rural Del. No. 1, Santa Barbara, Calif. Dec., 1896.
GARDNER, JAMES H., 626 Kennedy Bldg., Tulsa, Okla. Dec., 1911.
GARDNER, JULIA A., U. S. Geological Survey, Washington, D. C. Dec., 1920.
GEORGE, RUSSELL D., University of Colorado, Boulder, Colo. Dec., 1906.
GIDLEY, JAMES WILLIAM, U. S. Nat'l Museum, Washington, D. C. Dec., 1922.
GILES, ALBERT W., University of Virginia, University, Va. Dec., 1921.
GILL, ADAM CAPEN, Cornell University, Ithaca, N. Y. Dec., 1888.
GILMORE, CHARLES WHITNEY, U. S. National Museum, Washington, D. C. Dec., 1924.
GLENN, L. C., 2111 Garland Ave., Nashville, Tenn. June, 1900.
GOLDMAN, MARCUS ISAAC, U. S. Geol. Survey, Washington, D. C. Dec., 1916.
GOLDRING, WINIFRED, New York State Museum, Albany, N. Y. Dec., 1921.
GOLDTHWAIT, JAMES WALTER, Dartmouth College, Hanover, N. H. Dec., 1909.
GORDON, CHARLES H., University Library, University of Tennessee, Knoxville, Tenn. August, 1893.
GORDON, CLARENCE E., Massachusetts Agricultural College, Amherst, Mass. Dec., 1913.
GOULD, CHARLES N., 1218 Colcord Bldg., Oklahoma City, Okla. Dec., 1904.
GRABAU, AMADEUS W., Government University, Peking, China. Dec., 1898.
GRANGER, WALTER, American Museum of Natural History, New York, N. Y. Dec., 1911.
GRANT, ULYSSES SHERMAN, Northwestern Univ., Evanston, Ill. Dec., 1890.
GRASTY, JOHN SHARSHALL, Box 458, Charlottesville, Va. Dec., 1911.
GRATON, LOUIS C., Foxcroft House, Cambridge, 38, Mass. Dec., 1913.
GREGORY, HERBERT E., Yale University, New Haven, Conn. August, 1901.
GREENE, FRANK COOK, 1434 S. Cincinnati Ave., Tulsa, Okla. Dec., 1917.
GRIMSLEY, GEORGE P., 16 York Court, Baltimore, Md. August, 1895.
GROUT, FRANK F., University of Minnesota, Minneapolis, Minn. Dec., 1918.
GRUNER, JOHN W., University of Minnesota, Minneapolis, Minn. Dec., 1923.
GURLEY, WILLIAM F. E. R., University of Chicago, Chicago, Ill. Dec., 1914.
HALBERSTADT, BAIRD, Pottsville, Pa. Dec., 1909.
HANCE, J. H., 708 W. Washington Blvd., Urbana, Ill. Dec., 1920.
HANCOCK, E. T. Dec., 1919.
HARDER, E. C., 1111 Harrison Bldg., Philadelphia, Pa. Dec., 1918.
HARES, C. J., The Ohio Oil Co., Casper, Wyo. Dec., 1920.
HARRIS, GILBERT D., Cornell University, Ithaca, N. Y. Dec., 1903.
HARRISON, JOHN BURCHMORE, Georgetown, British Guiana. June, 1902.
HARTNAGEL, CHRIS A., Education Bldg., Albany, N. Y. Dec., 1913.
HASTINGS, JOHN B., 5456 Sierra Vista Ave., Los Angeles, Calif. May, 1889.
*HAWORTH, ERASMUS, University of Kansas, Lawrence, Kans.
HAY, OLIVER P., Carnegie Institution, Washington, D. C. Dec., 1921.
HAYES, ALBERT O., 719 Edificio Banco Boston, Buenos Aires, Argentina, South America. Dec., 1919.
HEALD, K. C., Kirtland Hall, Yale University, New Haven, Conn. Dec., 1920.
HENNEN, RAY V., 1701 Benedum-Trees Bldg., Pittsburgh, Pa. Dec., 1914.
HERSHEY, OSCAR H., Crocker Bldg., San Francisco, Calif. Dec., 1909.
HESS, FRANK L., U. S. Geological Survey, Washington, D. C. Dec., 1921.
HEWETT, DONNEL F., U. S. Geological Survey, Washington, D. C. Dec., 1916.

HICE, RICHARD R., Beaver, Pa. Dec., 1903.
HILL, J. M., U. S. Geological Survey, Washington, D. C. Dec., 1920.
*HILL, ROBERT T., 1239 N. Central Ave., Glendale, Calif.
HILLS, THOMAS MCDOUGALL, Vassar College, Poughkeepsie, N. Y. Dec., 1924.
HINDS, HENRY, Sinclair Oil Co., 120 Broadway, New York City. Dec., 1912.
HINTZE, FERDINAND FRIIS, 580 Corona St., Denver, Colo. Dec., 1917.
HOBBS, WILLIAM H., University of Michigan, Ann Arbor, Mich. August, 1891.
HOLDEN, ROY J., Virginia Polytechnic Institute, Blacksburg, Va. Dec., 1914.
HOLLAND, WILLIAM JACOB, Carnegie Museum, Pittsburgh, Pa. Dec., 1910.
HOLLICK, ARTHUR, N. Y. Botanical Garden, New York, N. Y. August, 1898.
HOPKINS, O. B., Internat. Petr. Co., Ltd., 56 Church St., Toronto, Canada. Dec., 1919.
HOPKINS, THOMAS C., Syracuse University, Syracuse, N. Y. Dec., 1894.
HOTCHKISS, WILLIAM OTIS, State Geological Surv., Madison, Wis. Dec., 1911.
HOWE, ERNEST, Litchfield, Conn. Dec., 1903.
HUBBARD, GEORGE D., Oberlin College, Oberlin, Ohio. Dec., 1914.
HUDSON, GEORGE H., Plattsburg Normal School, Plattsburg, N. Y. Dec., 1917.
HUME, GEORGE S., Geological Survey of Canada, Ottawa, Canada. Dec., 1923.
HUNT, WALTER F., University of Michigan, Ann Arbor, Mich. Dec., 1914.
HUNTINGTON, ELLSWORTH, Yale University, New Haven, Conn. Dec., 1906.
HUSSAKOF, LOUIS, 1537 50th St., Brooklyn, N. Y. Dec., 1910.
HYDE, J. E., Western Reserve University, Cleveland, Ohio. Dec., 1916.
JACKSON, ROBERT T., Peterborough, N. H. August, 1894.
JACOBS, ELBRIDGE C., University of Vermont, Burlington, Vt. Dec., 1921.
JEFFERSON, MARK S. W., Michigan State Normal College, Ypsilanti, Mich. Dec., 1904.
JEFFREY, EDWARD C., Harvard University, Cambridge, Mass. Dec., 1914.
JENKINS, OLAF P., State College, Pullman, Wash. Dec., 1921.
JOHANNSEN, ALBERT, University of Chicago, Chicago, Ill. Dec., 1908.
JOHNSON, B. L., U. S. Geological Survey, Washington, D. C. Dec., 1919.
JOHNSON, DOUGLAS WILSON, Columbia University, New York, N. Y. Dec., 1906.
JOHNSON, ROSWELL H., University of Pittsburgh, Pittsburgh, Pa. Dec., 1918.
JONAS, ANNA I., Room 4230, U. S. Geological Survey, Washington, D. C. Dec., 1922.
KATZ, FRANK JAMES, U. S. Geological Survey, Washington, D. C. Dec., 1912.
KAY, GEORGE FREDERICK, State Univ. of Iowa, Iowa City, Iowa. Dec., 1908.
KEITH, ARTHUR, U. S. Geological Survey, Washington, D. C. May, 1889.
*KEMP, JAMES F., Columbia University, New York, N. Y.
KENNEDY, WILLIAM, 2909 S. Jennings Ave., Fort Worth, Texas. Dec., 1923.
KEW, W. S. W., Box cor. Stocker and Jackson Sts., Glendale, Calif. Dec., 1920.
KEYES, CHARLES ROLLIN, 944 Fifth St., Des Moines, Iowa. August, 1890.
KINDLE, EDWARD M., Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.
KIRK, CHARLES T., Box 1592, Tulsa, Okla. Dec., 1915.
KIRK, EDWIN, U. S. Geological Survey, Washington, D. C. Dec., 1912.
KNIGHT, CYRIL WORKMAN, Nipissing Mining Co., Ltd., Cobalt, Ontario, Canada. Dec., 1911.
KNOPF, ADOLPH, Yale Station New Haven, Conn. Dec., 1911.
KNOPF, ELEANORA BLISS, 105 East Rock Road, New Haven, Conn. Dec., 1919.

KNOWLTON, FRANK H., U. S. National Museum, Washington, D. C. May, 1889.
KRAUS, EDWARD HENRY, Univ. of Michigan, Ann Arbor, Mich. June, 1902.
KUMMEL, HENRY B., Trenton, N. J. Dec., 1895.
*KUNZ, GEORGE F., 401 Fifth Ave., New York, N. Y.
LAHEE, FREDERIC H., American Exchange Natl. Bank Bldg., Dallas, Texas. Dec., 1917.
LANDES, HENRY, University of Washington, University Station, Seattle, Wash. Dec., 1908.
LANE, ALFRED C., Tufts College, Mass. Dec., 1889.
LARSEN, ESPER S., JR., Geol. Mus., Harvard Univ., Cambridge, Mass. Dec., 1914.
LAWSON, ANDREW C., University of California, Berkeley, Calif. May, 1889.
LEE, WILLIS THOMAS, U. S. Geological Survey, Washington, D. C. Dec., 1903.
LEES, JAMES H., Iowa Geological Survey, Des Moines, Iowa. Dec., 1914.
LEIGHTON, MORRIS M., Illinois Geological Survey, Urbana, Ill. Dec., 1921.
LEITH, CHARLES K., University of Wisconsin, Madison, Wis. Dec., 1902.
LEONARD, ARTHUR G., State University of North Dakota, Grand Forks, N. Dak. Dec., 1901.
LEVERETT, FRANK, Ann Arbor, Mich. August, 1890.
LEWIS, JOSEPH VOLNEY, Rutgers College, New Brunswick, N. J. Dec., 1906.
LIBBEY, WILLIAM, Princeton University, Princeton, N. J. August, 1899.
LIDDLE, RALPH ALEXANDER, Standard Oil Co. of Venezuela, Caracas, Venezuela, South America. Dec., 1921.
LINDGREN, WALDEMAR, Massachusetts Institute of Technology, Cambridge, Mass. August, 1890.
LISBOA, MIGUEL A. R., Caixa postal 829, Ave. Rio Branco 46-V, Rio de Janeiro, Brazil. Dec., 1913.
LITTLE, HOMER P., Clark University, Worcester, Mass. Dec., 1918.
LLOYD, E. R., First National Bank Bldg., Denver, Colo. Dec., 1919.
LOBECK, ARMIN KOHL, University of Wisconsin, Madison, Wis. Dec., 1924.
LOGAN, WILLIAM N., Indiana University, Bloomington, Ind. Dec., 1917.
LONGWELL, CHESTER R., Yale University, New Haven, Conn. Dec., 1923.
LOOMIS, FREDERICK BREWSTER, Amherst College, Amherst, Mass. Dec., 1909.
LOUDERBACK, GEORGE D., University of California, Berkeley, Calif. June, 1902.
LOUGHLIN, GERALD F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
LOW, ALBERT P., 154 McLaren St., Ottawa, Canada. Dec., 1905.
LULL, RICHARD SWANN, Yale University, New Haven, Conn. Dec., 1909.
LUPTON, CHARLES T., 611 17th St., Denver, Colo. Dec., 1916.
MCCALLIE, SAMUEL WASHINGTON, Atlanta, Ga. Dec., 1909.
MCCASKEY, HIRAM D., Central Point, Oregon. Dec., 1904.
MCCONNELL, RICHARD G., Rideau Club, Ottawa, Canada. May, 1889.
MCCOY, ALEX. W., 1020 Patterson Bldg., Denver, Colo. Dec., 1922.
MACDONALD, DONALD F., 45 Nassau St., New York City. Dec., 1915.
MACFARLANE, JAMES RIEMAN, Woodland Road, Pittsburgh, Pa. August, 1891.
MACKAY, BERTRAM R., Geological Survey, Ottawa, Canada. Dec., 1922.
MCKELLAR, PETER, Fort William, Ontario, Canada. August, 1890.
MCLAUGHLIN, DONALD H., 2239 Cedar St., Berkeley, Calif. Dec., 1922.
MCLEARN, FRANK HARRIS, Geological Survey, Ottawa, Canada. Dec., 1923.
MANSFIELD, GEORGE R., 2067 Park Rd. N. W., Washington, D. C. Dec., 1909.

MARBUT, CURTIS F., Bureau of Soils, Washington, D. C. August, 1897.
MARSTERS, VERNON F., 123 Railway Exchange Bldg., Kansas City, Mo. Aug., 1892.
MARTIN, GEORGE C., U. S. Geological Survey, Washington, D. C. June, 1902.
MARTIN, LAWRENCE, Dept. of State, Room 381, Washington, D. C. Dec., 1909.
MATHER, KIRTLEY F., Harvard Geological Museum, Cambridge, Mass., Dec., 1918.
MATHEWS, EDWARD B., Johns Hopkins University, Baltimore, Md. Aug., 1895.
MATSON, GEORGE C., 408 Cosden Bldg., Tulsa, Okla. Dec., 1918.
MATTHES, FRANCOIS E., U. S. Geol. Survey, Washington, D. C. Dec., 1914.
MATTHEW, W. D., American Museum of Natural History, New York, N. Y. Dec., 1903.
MAURY, CARLOTTA J., Hastings-on-Hudson, N. Y. Dec., 1920.
MAYNARD, THOMAS POOLE, 1622 D. Hurt Bldg., Atlanta, Ga. Dec., 1914.
MEAD, WARREN JUDSON, University of Wisconsin, Madison, Wis. Dec., 1916.
MEHL, MAURICE G., University of Missouri, Columbia, Mo. Dec., 1922.
MEINZER, OSCAR E., U. S. Geological Survey, Washington, D. C. Dec., 1916.
MENDENHALL, WALTER C., U. S. Geol. Survey, Washington, D. C. June, 1902.
MERRIAM, JOHN C., Carnegie Institution, Washington, D. C. August, 1895.
MERRILL, GEORGE P., U. S. National Museum, Washington, D. C. Dec., 1888.
MERTIE, JOHN BEAVER, JR., 112 Park Ave., Takoma Park, D. C. Dec., 1923.
MERWIN, HERBERT E., Geophysical Laboratory, Washington, D. C. Dec., 1914.
MILLER, ARTHUR M., State University of Kentucky, Lexington, Ky. Dec., 1897.
MILLER, BENJAMIN L., Lehigh University, Bethlehem, Pa. Dec., 1904.
MILLER, WILLIAM JOHN, University of California, Southern Branch, Los Angeles, Calif. Dec., 1909.
MISER, HUGH D., U. S. Geological Survey, Washington, D. C. Dec., 1916.
MOFFIT, FRED HOWARD, U. S. Geological Survey, Washington, D. C. Dec., 1912.
MOORE, ELWOOD S., University of Toronto, Toronto, Canada. Dec., 1911.
MOORE, RAYMOND C., University of Kansas, Lawrence, Kans. Dec., 1921.
MOOK, CHARLES C., Metuchen, N. J. Dec., 1922.
MUNN, MALCOLM JOHN, Clinton Bldg., Tulsa, Okla. Dec., 1909.
*NASON, FRANK L., West Haven, Conn.
NELSON, W. A., Tennessee Geological Survey, Nashville, Tenn. Dec., 1920.
NEWLAND, DAVID HALE, Albany, N. Y. Dec., 1906.
NEWSOM, JOHN F., Leland Stanford Jr. University, Stanford University, Calif. Dec., 1899.
NOBLE, LEVI F., Valyermo, Calif. Dec., 1916.
NORTON, WILLIAM H., Cornell College, Mount Vernon, Iowa. Dec., 1895.
NORWOOD, CHARLES J., State University, Lexington, Ky. August, 1894.
O'CONNELL, MARJORIE, 1123 Calhoun Ave., New York City. Dec., 1919.
OGILVIE, IDA HELEN, Barnard College, Columbia University, New York, N. Y. Dec., 1906.
O'HARA, CLEOPHAS C., South Dakota School of Mines, Rapid City, S. Dak. Dec., 1904.
OHERN, DANIEL WEBSTER, 515 W. 14th St., Oklahoma City, Okla. Dec., 1911.
O'NEILL, J. J., McGill University, Montreal, Canada. Dec., 1920.
OSBORN, HENRY F., American Museum of Natural History, New York, N. Y. August, 1894.

OVERBECK, ROBERT M., c/o Caracoles Tin Co. of Bolivia, Casilla No. 674, La Paz, Bolivia, South America. Dec., 1921.

PACK, ROBERT W., Box 790, Beaumont, Texas. Dec., 1916.

PAIGE, SIDNEY, U. S. Geological Survey, Washington, D. C. Dec., 1911.

PALACHE, CHARLES, Harvard University, Cambridge, Mass. August, 1897.

PARKS, WILLIAM A., University of Toronto, Toronto, Canada. Dec., 1906.

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PECK, FREDERICK B., Lafayette College, Easton, Pa. August, 1901.

PENROSE, RICHARD A. F., JR., Bullitt Bldg., Philadelphia, Pa. May, 1889.

PERKINS, GEORGE H., University of Vermont, Burlington, Vt. June, 1902.

PERRY, JOSEPH H., 276 Highland St., Worcester, Mass. Dec., 1888.

PHALEN, WILLIAM C., 61 Broadway, New York, N. Y. Dec., 1912.

PHILLIPS, ALEXANDER H., Princeton University, Princeton, N. J. Dec., 1914.

POGUE, JOSEPH E., 42 West 12th St., New York City. Dec., 1911.

POWERS, SIDNEY, Amerada Petr. Corp., Tulsa, Okla. Dec., 1920.

PRATT, JOSEPH H., North Carolina Geol. Survey, Chapel Hill, N. C. Dec., 1898.

PRATT, W. E., Humble Oil and Refining Co., Houston, Texas. Dec., 1920.

PRICE, WILLIAM A., 409 Anita St., Houston, Texas. Dec., 1916.

PRINDLE, LOUIS M., U. S. Geological Survey, Washington, D. C. Dec., 1912.

PROUTY, WILLIAM F., Univ. of North Carolina, Chapel Hill, N. C. Dec., 1911.

QUIRKE, TERENCE T., University of Illinois, Urbana, Ill. Dec., 1921.

RANSOME, FREDERICK L., University Station, Tucson, Ariz. August, 1895.

RAYMOND, PERCY EDWARD, Museum of Comparative Zoology, Cambridge, Mass. Dec., 1907.

REBER, LOUIS E., Box 1096, Jerome, Ariz. Dec., 1923.

REEDS, CHESTER A., American Museum of Natural History, New York, N. Y. Dec., 1913.

REESIDE, JOHN B., JR., U. S. Geological Survey, Hyattsville, Md. Dec., 1921.

REEVES, FRANK, U. S. Geological Survey, Washington, D. C. Dec., 1924.

REGER, DAVID B., Box 816, Morgantown, W. Va. Dec., 1918.

REID, HARRY FIELDING, Johns Hopkins University, Baltimore, Md. Dec., 1892.

REINECKE, LEOPOLD, P. O. Box 2682, Johannesburg, Transvaal, South Africa. Dec., 1916.

RICE, WILLIAM NORTH, Wesleyan University, Middletown, Conn. Aug., 1890.

RICH, JOHN LYON, Box 3, Ottawa, Kans. Dec., 1912.

RICHARDS, R. W., U. S. Geological Survey, Washington, D. C. Dec., 1920.

RICHARDSON, CHARLES H., Syracuse University, Syracuse, N. Y. Dec., 1899.

RICHARDSON, GEORGE B., U. S. Geol. Survey, Washington, D. C. Dec., 1908.

RIES, HEINRICH, Cornell University, Ithaca, N. Y. Dec., 1893.

RIGGS, ELMER S., Field Museum of Natural History, Chicago, Ill. Dec., 1911.

ROBINSON, HENRY HOLLISTER, Yale University, Hopkins Hall, New Haven, Conn. Dec., 1916.

RODDY, H. J., State Normal School, Millersville, Pa. Dec., 1919.

ROGERS, AUSTIN F., Stanford University, Calif. Dec., 1918.

ROSE, BRUCE, Department of Geology, Queens University, Kingston, Ontario, Canada. Dec., 1916.

RUEDEMANN, RUDOLF, Albany, N. Y. Dec., 1905.

RUTLEDGE, JOHN JOSEPH, State Bureau of Mines, 22 Light St., Baltimore, Md. Dec., 1911.

SALES, RENO H., Anaconda Copper Mining Co., Butte, Mont. Dec., 1916.
SAMPSON, EDWARD, U. S. Geological Survey, Washington, D. C. Dec., 1924.
SAYLES, ROBERT WILCOX, Harvard University, Chestnut Hill, Mass. Dec., 1917.
SARDESON, FREDERICK W., Univ. of Minnesota, Minneapolis, Minn. Dec., 1892.
SAVAGE, THOMAS EDMUND, University of Illinois, Urbana, Ill. Dec., 1907.
SCHALLER, WALDEMAR T., U. S. Geol. Survey, Washington, D. C. Dec., 1918.
SCHOFIELD, S. J., University of British Columbia, Vancouver, B. C. Dec., 1918.
SCHRADER, FRANK C., U. S. Geological Survey, Washington, D. C. Aug., 1901.
SCHUCHERT, CHARLES, Yale University, New Haven, Conn. August, 1895.
SCHULTZ, ALFRED R., Hudson, Wis. Dec., 1912.
SCHWARTZ, GEORGE M., Univ. of Minnesota, Minneapolis, Minn. Dec., 1923.
SCOTT, IRVING D., University of Michigan, Ann Arbor, Mich. Dec., 1923.
SCOTT, WILLIAM B., Princeton University, Princeton, N. J. August, 1892.
SEAMAN, ARTHUR E., Michigan College of Mines, Houghton, Mich. Dec., 1904.
SEARS, JULIAN DUCKER, 209 E. Underwood St., Chevy Chase, Md. Dec., 1924.
SELLARDS, ELIAS H., University of Texas, Austin, Texas. Dec., 1905.
SEMMES, DOUGLAS R., Apartado postal, 150, Tampico, Tamaulipas, Mexico. Dec., 1921.
SHALER, MILLARD K., 66 Rue Des Colonies, Brussels, Belgium. Dec., 1914.
SHANNON, CHARLES W., Bureau of Geology, Norman, Okla. Dec., 1918.
SHATTUCK, GEORGE BURBANK, 24 E. Mt. Vernon Place, Baltimore, Md. Aug., 1899.
SHAW, EUGENE W., 170 Broadway, New York, N. Y. Dec., 1912.
SHEDD, SOLON, State College of Washington, Pullman, Wash. Dec., 1904.
SHEPARD, EDWARD M., 1403 Benton Ave., Springfield, Mo. August, 1901.
SHIMEK, BOHUMIL, University of Iowa, Iowa City, Iowa. Dec., 1904.
SHIMER, HERVEY WOODBURN, Massachusetts Institute of Technology, Cambridge, Mass. Dec., 1910.
SHULER, E. W., South Methodist University, Dallas, Texas. Dec., 1920.
SIEBENTHAL, CLAUDE E., U. S. Geol. Survey, Washington, D. C. Dec., 1912.
*SIMONDS, FREDERICK W., University of Texas, Austin, Texas.
SIMPSON, HOWARD E., University of North Dakota, Grand Forks, N. Dak. Dec., 1923.
SINCLAIR, WILLIAM JOHN, Princeton University, Princeton, N. J. Dec., 1906.
SINGEWALD, JOSEPH T., Johns Hopkins University, Baltimore, Md. Dec., 1911.
SLOAN, EARLE, Charleston, S. C. Dec., 1908.
SMITH, BURNETT, Syracuse University, Syracuse, N. Y. Dec., 1911.
SMITH, CARL, Box 1136, Tulsa, Okla. Dec., 1912.
*SMITH, EUGENE A., University of Alabama, University, Ala.
SMITH, GEORGE OTIS, U. S. Geological Survey, Washington, D. C. Aug., 1897.
SMITH, PHILIP S., U. S. Geological Survey, Washington, D. C. Dec., 1909.
SMITH, RICHARD A., Biological Survey of Michigan, Lansing, Mich. Dec., 1921.
SMITH, STANLEY, University of Bristol, Bristol, England. Dec., 1922.
SMITH, WARREN DU PRÉ, University of Oregon, Eugene, Ore. Dec., 1909.
SMITH, W. S. TANGIER, 640 Tennyson Ave., Palo Alto, Calif. June, 1902.
*SMOCK, JOHN C., Hudson, N. Y.
SMYTH, CHARLES H., JR., Princeton University, Princeton, N. J. Aug., 1892.
SMYTH, HENRY L., Harvard University, Cambridge, Mass. August, 1894.

SOMERS, R. E., Oil and Gas Bldg., University of Pittsburgh, Pittsburgh, Pa. Dec., 1919.

SOPER, EDGAR K., c/o Sinclair Expl. Co., 45 Nassau St., New York City. Dec., 1918.

SOSMAN, R. B., Geophysical Laboratory, Washington, D. C. Dec., 1920.

SPEIGHT, ROBERT, Canterbury College, Christ Church, New Zealand. Dec., 1916.

SPENCER, ARTHUR COE, U. S. Geological Survey, Washington, D. C. Dec., 1896.

SPIEKER, EDMUND MAUTE, U. S. Geological Survey, Washington, D. C. Dec., 1924.

SPRINGER, FRANK, U. S. National Museum, Washington, D. C. Dec., 1911.

SPURR, JOSIAH E., c/o Engineering and Mining Journal, 10th Ave. and 36th St., New York, N. Y. Dec., 1894.

STANLEY-BROWN, JOSEPH, 26 Exchange Place, New York, N. Y. August, 1892.

STANTON, TIMOTHY W., U. S. Nat'l Museum, Washington, D. C. August, 1891.

STAUFFER, CLINTON R., Univ. of Minnesota, Minneapolis, Minn. Dec., 1911.

STEBINGER, EUGENE, JR., 719 Edificio Banco Boston, Buenos Aires, Argentina. Dec., 1916.

STEIPTMANN, EDWARD, 13 White St., Lexington, Va. Dec., 1916.

STEPHENSON, LLOYD W., U. S. Geol. Survey, Washington, D. C. Dec., 1911.

STOLLER, JAMES HOUGH, Union College, Schenectady, N. Y. Dec., 1917.

STONE, RALPH WALTER, State Geological Survey, Harrisburg, Pa. Dec., 1912.

STOSE, GEORGE WILLIS, U. S. Geological Survey, Washington, D. C. Dec., 1908.

STOUT, WILBER, Geological Survey of Ohio, Columbus, Ohio. Dec., 1918.

SWARTZ, CHARLES K., Johns Hopkins University, Baltimore, Md. Dec., 1908.

TABER, STEPHEN, University of South Carolina, Columbia, S. C. Dec., 1914.

TAFF, JOSEPH A., 629 Cooper St., Palo Alto, Calif. August, 1895.

TALBOT, MIGNON, Mount Holyoke College, South Hadley, Mass. Dec., 1913.

TALMAGE, JAMES E., Durham House, Edge Lane, Liverpool, England. Dec., 1897.

TARR, WILLIAM ARTHUR, University of Missouri, Columbia, Mo. Dec., 1917.

TAYLOR, FRANK B., 420 Downing Ave., Fort Wayne, Ind. Dec., 1895.

THOM, WILLIAM TAYLOR, JR., U. S. Geological Survey, Washington, D. C. Dec., 1924.

THOMAS, ABRAM O., University of Iowa, Iowa City, Iowa. Dec., 1921.

THORPE, MALCOLM R., 1463 Yale Station, New Haven, Conn. Dec., 1923.

TILTON, J. L., Morgantown, W. Va. Dec., 1920.

TOMLINSON, CHARLES WELDON, 1610 Bixby Ave., Ardmore, Okla. Dec., 1917.

TROWBRIDGE, ARTHUR C., State Univ. of Iowa, Iowa City, Iowa. Dec., 1913.

TROXELL, EDWARD L., Yale Station, New Haven, Conn. Dec., 1923.

*TURNER, HENRY W., Mills Bldg., San Francisco, Calif.

TWENHOFEL, WILLIAM H., University of Wisconsin, Madison, Wis. Dec., 1913.

TWITCHELL, MAYVILLE W., State Geological Survey, Trenton, N. J. Dec., 1911.

TYRRELL, JOSEPH B., Confederation Life Bldg., Toronto, Canada. May, 1889.

UDDEN, JOHAN A., University of Texas, Austin, Texas. August, 1897.

UGLOW, WILLIAM L., University of British Columbia, Vancouver, B. C. Dec., 1922.

ULRICH, EDWARD O., U. S. Geological Survey, Washington, D. C. Dec., 1903.

UMPLEBY, JOSEPH B., University of Oklahoma, Norman, Okla. Dec., 1913.

*UPHAM, WARREN, Minnesota Historical Society, Saint Paul, Minn.
VAN HORN, F. R., Case School of Applied Science, Cleveland, Ohio. Dec., 1898.
VAN INGEN, GILBERT, Princeton University, Princeton, N. J. Dec., 1904.
VAN TUYL, FRANCIS M., Colorado School of Mines, Golden, Colo. Dec., 1917.
VAUGHAN, T. WAYLAND, Scripps Institution, La Jolla, Calif. August, 1896.
VEATCH, ARTHUR CLIFFORD, 7 Central Drive, Port Washington, N. Y. Dec., 1906.
VISHER, STEPHEN S., 817 E. Second St., Bloomington, Ind. Dec., 1923.
WADE, BRUCE, State Geological Survey, Nashville, Tenn. Dec., 1920.
*WALCOTT, CHARLES D., Smithsonian Institution, Washington, D. C.
WALKER, THOMAS L., University of Toronto, Toronto, Canada. Dec., 1903.
WARD, LEONARD KEITH, Department of Mines, Adelaide, South Australia. Dec., 1924.
WARING, GERALD A., Margay Oil Corp., Box 2103, Tulsa, Okla. Dec., 1921.
WARREN, CHARLES H., Yale University, New Haven, Conn. Dec., 1901.
WASHBURNE, C. W., 2 Rector St., New York, N. Y. Dec., 1919.
WASHINGTON, HENRY S., Geophysical Laboratory, Washington, D. C. Aug., 1896.
WEAVER, CHARLES E., 264 Herkimer Road, Utica, N. Y. Dec., 1913.
WEED, WALTER H., Tuckahoe, N. Y. May, 1889.
WEGEMANN, CARROLL H., P. O. Box 240, Denver, Colo. Dec., 1912.
WEIDMAN, SAMUEL, 814 Monett St., Norman, Okla. Dec., 1903.
WELLER, STUART, University of Chicago, Chicago, Ill. June, 1900.
WELLS, ROGER C., U. S. Geological Survey, Washington, D. C. Dec., 1921.
WENTWORTH, CHESTER K., Iowa State University, Iowa City, Iowa. Dec., 1923.
WESTGATE, LEWIS G., 124 Oak Hill Ave., Delaware, Ohio. August, 1894.
WHERRY, EDGAR T., Bureau of Chemistry, Washington, D. C. Dec., 1915.
WHITE, DAVID, U. S. National Museum, Washington, D. C. May, 1889.
*WHITE, ISRAEL C., Morgantown, W. Va.
WHITLOCK, H. P., Amer. Museum of Natural History, N. Y. City. Dec., 1920.
WHITNEY, FRANCIS L., University of Texas, Austin, Texas. Dec., 1923.
WIELAND, GEORGE REBER, Yale University, New Haven, Conn. Dec., 1910.
WILDER, FRANK A., North Holston, Smyth County, Va. Dec., 1905.
*WILLIAMS, EDWARD H., JR., Woodstock, Vt.
WILLIAMS, IRA A., 821 Spalding Bldg., Portland, Ore. Dec., 1905.
WILLIAMS, MERTON YARWOOD, Univ. of British Columbia, Vancouver, B. C. Dec., 1916.
WILLIS, BAILEY, Leland Stanford Jr. University, Stanford University, Calif. Dec., 1889.
WILSON, ALFRED W. G., Department of Mines, Ottawa, Canada. June, 1902.
WILSON, MORLEY EVANS, Geological Survey, Ottawa, Canada. Dec., 1916.
WINCHELL, ALEXANDER N., University of Wisconsin, Madison, Wis. Aug., 1901.
*WINSLOW, ARTHUR, 131 State St., Boston, Mass.
WOLFF, JOHN E., Harvard University, Cambridge, Mass. Dec., 1889.
WOOD, HARRY OSCAR, Mt. Wilson Observatory, Pasadena, Calif. Dec., 1922.
WOODMAN, JOSEPH E., New York University, New York, N. Y. Dec., 1905.
WOODRING, WENDELL P., U. S. Geol. Survey, Washington, D. C. Dec., 1921.

WOODRUFF, E. G., 1611 S. Detroit St., Tulsa, Okla. Dec., 1922.

WOODWORTH, JAY B., Geological Museum, 38 Oxford St., Cambridge, Mass. Dec., 1895.

WOOLNOUGH, WALTER GEORGE, "Callabonna," Florence St., Killara, New South Wales. Dec., 1924.

WRATHER, WILLIAM E., 6044 Bryan Parkway, Dallas, Texas. Dec., 1923.

WRIGHT, CHARLES WILL, 28 Vie del Parliamento, Rome, Italy. Dec., 1909.

WRIGHT, FREDERIC E., Geophysical Laboratory, Washington, D. C. Dec., 1903.

CORRESPONDENTS DECEASED

Capellini, Giovanni. Died 1924.
Credner, Herman. Died July 22, 1913.
De Stefani, Carlo. Died Dec. 12, 1924.
Geikie, Sir Archibald. Died Nov., 1924.
Michel-Lévy, A. Died September, 1911.
Rosenbusch, H. Died January 20, 1914.
Suess, Edward. Died April 20, 1914.
Teall, Sir J. J. H. Died July 2, 1924.
Tietze, Emil. Died —, 1924.
Tschernyschew, Th. Died Jan. 15, 1914.
Zirkel, Ferdinand. Died June 11, 1912.

FELLOWS DECEASED

* Indicates Original Fellow (see article III of Constitution)

*Ashburner, Chas. A. Died Dec. 24, 1889.
Barlow, Alfred E. Died May 28, 1914.
Barrell, Joseph. Died May 4, 1919.
Beecher, Charles E. Died Feb. 14, 1904.
*Becker, George F. Died April 20, 1919.
Bell, Robert. Died June 18, 1917.
Bickmore, Albert S. Died Aug. 12, 1914.
Blake, Wm. Phipps. Died May 21, 1910.
Bowman, Amos. Died June 18, 1894.
*Branner, John C. Died March 1, 1922.
Brooks, Alfred H. Died Nov. 22, 1924.
Brown, Amos P. Died Oct. 9, 1917.
Buckley, Ernest R. Died Jan. 19, 1912.
Cairnes, D. D. Died June 14, 1917.
*Calvin, Samuel. Died April 17, 1911.
Carpenter, Frank R. Died April 1, 1910.
Castillo, Antonio Del. Died Oct.28,1895.
Chapin, J. H. Died March 14, 1892.
Clark, William B. Died July 27, 1917.
*Claypole, Edward W. Died Aug. 17, 1901.
*Comstock, Theo. B. Died July 26, 1915.
Cook, George H. Died Sept. 22, 1889.
*Cope, Edward D. Died April 12, 1897.
Cox, George H. Died August 20, 1922.
*Cushing, H. P. Died April 14, 1921.
*Dana, James D. Died April 14, 1895.
Davis, Charles A. Died April 9, 1916.
Dawson, George M. Died March 2, 1901.
Dawson, Sir J. Wm. Died Nov. 19, 1899.
Derby, Orville A. Died Nov. 27, 1915.
Drysdale, Chas. W. Died July 10, 1917.
Dutton, Clarence E. Died Jan. 4, 1912.
*Dwight, Wm. B. Died Aug. 29, 1906.
Eastman, Chas. R. Died Sept. 27, 1918.
*Eldridge, George H. Died June 29, 1905.
*Emmons, Samuel F. Died March 28, 1911.
Fontaine, Wm. M. Died April 30, 1913.
*Foote, Albert E. Died October 10, 1895.
*Frazer, Persifor. Died April 7, 1909.
*Fuller, Homer T. Died Aug. 14, 1908.
*Gilbert, Grove K. Died May 1, 1918.
Giroux, N. J. Died November 30, 1891.
Hague, Arnold. Died May 14, 1917.
*Hall, Christopher W. Died May10, 1911.
*Hall, James. Died August 7, 1898.
Hatcher, John B. Died July 3, 1904.
*Hay, Robert. Died December 14, 1895.
Hayes, C. Willard. Died Feb. 9, 1916.
*Heilprin, Angelo. Died July 17, 1907.
Hilgard, Eugene W. Died Jan. 8, 1916.
Hill, Frank A. Died July 13, 1915.
Hills, Richard C. Died Aug. 14, 1923.
*Hitchcock, Chas. H. Died Nov. 7, 1919.
*Holbrook, Levi. Died July 26, 1922.
*Holmes, Joseph A. Died July 13, 1915.
Honeyman, David. Died Oct. 17, 1889.
*Hovey, Edmund O. Died Sept. 27, 1924.
*Hovey, Horace C. Died July 27, 1914.
*Howell, Edwin E. Died April 16, 1911.
Hunt, Thomas S. Died Feb. 12, 1892.
*Hyatt, Alpheus. Died Jan. 15, 1902.
Iddings, J. P. Died Sept. 8, 1920.
Irving, John D. Died July 26, 1918.
Jackson, Thomas M. Died Feb. 3, 1912.
*James, Joseph F. Died March 29, 1897.
Julien, Alexis A. Died May 7, 1919.
Knight, Wilbur C. Died July 28, 1903.
Lacoe, Ralph D. Died February 5, 1901.
Laflamme, J. C. K. Died July 6, 1910.
Lambe, L. M. Died March 12, 1919.
Langton, Daniel W. Died June 21, 1909.
*Le Conte, Joseph. Died July 6, 1901.
*Lesley, J. Peter. Died June 2, 1903.
Loughridge, Robt. H. Died July 1, 1917.
McCalley, Henry. Died Nov. 20, 1904.
*McGee, W J. Died September 4, 1912.
McInnes, William. Died March 10, 1925.
Marcy, Oliver. Died March 19, 1899.
Marsh, Othniel C. Died March 18, 1899.
Mell, P. H. Died October 12, 1918.
*Merrill, Fred. J. H. Died Nov. 29, 1916.
Miller, Willet G. Died Feb. 4, 1925.
Mills, James E. Died July 25, 1901.
*Nason, Henry B. Died Jan. 17, 1895.
*Neff, Peter. Died May 11, 1903.
*Newberry, John S. Died Dec. 7, 1892.
Niles, William H. Died Sept. 12, 1910.
*Orton, Edward. Died October 16, 1899.
*Osborn, Amos O. Died March, 1911.
*Owen, Richard. Died March 24, 1890.
Penfield, Samuel L. Died Aug. 14, 1906.
Penhallow, David P. Died Oct. 20, 1910.
Pirsson, L. V. *Died Dec. 8, 1919.
*Platt, Franklin. Died July 24, 1900.
Pettee, William H. Died May 26, 1904.
*Powell, John W. Died Sept. 23, 1902.

*Prosser, Chas. S. Died Sept. 11, 1916.
*Pumpelly, Raphael. Died August, 1923.
Purdue, A. H. Died Dec. 12, 1917.
Rogers, G. S. Died Nov. 18, 1919.
*Russell, Israel C. Died May 1, 1906.
*Safford, James M. Died July 3, 1907.
Saint John, O. H. Died July 17, 1921.
*Salisbury, Rollin D. Died Aug. 15, 1922.
*Schaeffer, Charles. Died Nov. 23, 1903.
Seely, H. M. Died May 4, 1917.
Seña, J. C. da Costa. Died June 20, 1919.
*Shaler, Nathaniel S. Died Apr. 10, 1906.
*Spencer, J. W. Died October 9, 1921.
*Stevenson, John J. Died Aug. 10, 1924.
Sutton, William J. Died May 9, 1915.
Tarr, Ralph S. Died March 21, 1912.
Tight, William G. Died Jan. 15, 1910.
*Todd, James E. Died October 29, 1922.
*Van Hise, C. R. Died Nov. 19, 1918.
*Vogdes, Anthony W. Died Feb. 8, 1923.
Wachsmuth, Chas. Died Feb. 7, 1896.
Wadsworth, M. E. Died April 21, 1921.
Watson, Thomas L. Died Nov. 10, 1924.
Weston, Thomas C. Died July 20, 1910.
White, Theodore G. Died July 7, 1901.
*Whitfield, Robt. P. Died April 6, 1910.
*Williams, George H. Died July 12, 1894.
*Williams, J. Francis. Died Nov. 9, 1891.
*Williams, H. S. Died July 31, 1918.
Wilmott, Arthur B. Died May 8, 1914.
*Winchell, Alex. Died Feb. 19, 1891.
*Winchell, H. V. Died July 28, 1923.
*Winchell, Newton H. Died May 1, 1914.
Woodward, Robt. S. Died June 29, 1924.
Wright, Albert A. Died April 2, 1905.
*Wright, G. F. Died April 20, 1921.
Yeates, William S. Died Feb. 19, 1908.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PROCEEDINGS OF THE TWENTY-THIRD ANNUAL MEETING OF THE CORDILLERAN SECTION OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT STANFORD UNIVERSITY, CALIFORNIA, MAY 2 AND 3, 1924.

JOHN P. BUWALDA, *Secretary*

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Session of Friday, May 2

The Cordilleran Section of the Geological Society of America held its twenty-third annual meeting at Stanford University on Friday afternoon and Saturday morning and afternoon, May 2 and 3, 1924, in conjunction with the Le Conte Club.

In the absence of Chairman F. M. Anderson, Eliot Blackwelder presided at the Friday afternoon session and Robert Anderson acted as chairman at the Saturday sessions.

Election of officers

The following officers were nominated, and subsequently elected by a mail ballot, to serve for the year 1924-25:

Chairman, Warren D. Smith
Secretary, John P. Buwalda
Councilor, Eliot Blackwelder

Session of Friday Afternoon, May 2

Program of papers

MARINE LOWER TRIASSIC BEDS OF UTAH

BY ASA A. L. MATTHEWS

(*Abstract*)

This paper calls attention to the Anasibirites bed of the Wasatch Range, Utah. It compares the species with those of similar beds described in the Salt Range, India, and also those of Timor. The paper states that the Anasibirites bed represents a horizon near the top of the Lower Triassic and fills in a gap between the Meekoceras and Columbites zones which occur in the type section in the Aspin Mountains, Idaho, and also in the Inyo Range, California. The general conclusion reached is that, with the exception of the lowermost bed, America possesses complete faunas representing the Lower Triassic.

Discussed by Messrs. J. P. Smith, Blackwelder, and Taff.

GEOLOGIC SECTION ACROSS THE MIDDLE SALINAS VALLEY OF CALIFORNIA FROM THE SAN ANTONIO RIVER TO SAN LORENZO CREEK

BY WILLIAM M. NICHOLLS

(*Abstract*)

The formations represented in the section are the Santa Lucia complex, the Martinez-Eocene, Vaqueros-Miocene, Salinas Shale-Miocene, Santa Margarita-Miocene, Paso Robles-Pliocene, and Quaternary.

This section contrasts the great difference in structure of the Tertiary rocks on the two sides of the valley. On the west there has been strong folding and both normal and thrust faulting. On the east the strata have been only gently folded. The study throws some light on the origin of the Santa Lucia Range and the southern portion of the Gabilan Range. It establishes the fact that the major part of the folding and faulting that has given the Santa Lucia Range its present height occurred in post-Upper Miocene time.

The ruggedness of the region west of the valley and the striking evenness of the profile to the east indicate a marked difference in physiographic history.

Read from manuscript. Illustrated with map and section. Discussed by Messrs. Blackwelder, Willis, Taff, and Clark.

DISCOVERY OF MAMMALIAN REMAINS IN SESPE BEDS NEAR SANTA PAULA, CALIFORNIA

BY CHESTER STOCK

(*Abstract*)

The Sespe deposits have been noted for their lack of vertebrate remains. Recently a few specimens indicating a *Hypertragulus*-like form have been found in the Sespe of South Mountain near Santa Paula, Ventura County, California.

Presented extemporaneously. Discussed by Mr. Clark.

RECENT DISCOVERY OF HUMAN REMAINS IN LOS ANGELES, CALIFORNIA

BY CHESTER STOCK

(*Abstract*)

Trenching for the north outfall sewer of the city of Los Angeles has uncovered human remains under conditions suggesting antiquity. Study of the geologic features of the region as seen in the exposures along the trench lines determines the probable age of the deposits containing the human remains.

Presented from notes. Illustrated with lantern slides. Discussed by Messrs. Willis, Robt. Anderson, and Taff.

CLASTIC DIKES OF SOUTHEASTERN WASHINGTON

BY OLAF P. JENKINS

(*Abstract*)

Many curious sand and dust dikes occur in southeastern Washington, especially in a region west of Walla Walla. Those near Touchet occupy fissures in loess deposits and in stream terraces of cross-bedded sands and gravels. The dikes are structurally arranged in layers which lie parallel to the walls of the fissures. Some of the dikes are as thin as paper, while others are several feet thick, and all have a tendency to branch. Their materials are of water-worn basaltic sand and volcanic glass dust. The fissures might have been formed by earthquakes and their subsequent filling undoubtedly came from above. Their age is postglacial.

Read by title.

GEOLOGY OF STEENS AND PUEBLO MOUNTAINS, SOUTHEASTERN OREGON

BY WARREN D. SMITH

(*Abstract*)

Following a statement of the observations made by Russell, Davis, and Waring in this region, the author gives a general summary of the geologic and physiographic history of southeastern Oregon, with a tentative table of stratigraphy of that region. The additional contributions to the geology of Steens and Pueblo Mountains consist of data regarding glaciation on Steens Mountain, thus reenforcing Russell's early observations. Russell had noted glaciation only in the canyon of the Keiger, on the northwest side of Steens Mountain. Evidences for glaciation were found in other canyons, especially the Wildhorse, on the south side of Steens Mountain, by the author.

The structure of Steens Mountain is elaborated with a general conclusion that this is not a case of normal faulting simply, though there may be some faulting of that kind, but the mountain owes its origin largely to thrust-faulting attendant upon folding. The finding of a thousand feet of tuffs at the base of the lavas on Steens Mountain would seem to point to their correlation with the John Day (Oligocene) farther north in the State. Definite evidence for this correlation has not yet been obtained. A suite of specimens of the lavas of Steens Mountain has been described, and these seem to differ rather remarkably from the ordinary facies of Columbia lava. Some of these specimens are quite noteworthy in their having very large phenocrysts of labradorite, over two inches long and nearly that in width, but quite thin and tabular. These are embedded in a very definitely holocrystalline groundmass.

Additional notes on the geology, lithology, and economic geology of Pueblo Mountain conclude the paper. This presentation was merely a preliminary statement of the final paper, which, it is hoped, will appear after the next summer's field-work.

Read from manuscript and illustrated with lantern slides. Discussed by Messrs. Willis and Buwalda.

PHYSIOGRAPHY OF THE EUGENE QUADRANGLE, OREGON

BY HUBERT G. SCHENCK

(*Abstract*)

The flat-floored Willamette Valley, isolated buttes within the valley, and the braided stream of the Willamette River are the dominant features of the region near Eugene, Oregon. These features are discussed in connection with the geology of the quadrangle.

Presented extemporaneously.

DISCUSSION

Mr. WARREN D. SMITH: I should like to call attention to another feature, in connection with the Willamette Valley, which Mr. Schenck has not mentioned and which really does not fall within the Eugene Quadrangle.

Farther down the valley, on either side, but particularly on the east side of the valley, in the neighborhood of Lebanon and farther to the north, there are evidences of an older peneplanation several hundred feet above the valley floor. This old peneplain is sloping gently toward the valley.

A question has been asked about the erratics on the Willamette Valley floor. I should like to suggest that we may not have exhausted all the possible explanations other than the Willamette Sound iceberg theory. It may be that a larger stream than anything now flowing in the valley has had something to do with spreading these boulders about. With our present knowledge, we are not in a position to say that the Willamette Sound theory is not the explanation we must fall back on.

SESSION OF SATURDAY, MAY 3

RECENT SEISMIC ACTIVITY IN CENTRAL CALIFORNIA

BY JAMES B. MACELWANE

(*Abstract*)

The most important recent shock on the San Andreas fault was the Corralitos earthquake of September 19, 1923. In the Mount Hamilton Range slight earthquakes have become very frequent. The swarm of the middle of August, 1923, and the group which included the stronger shock of April 3, 1924, deserve special mention.

Presented extemporaneously.

DISCUSSION

Mr. WARREN D. SMITH: Father Macelwane has presented a most interesting paper, but for once California can not claim the record for the number of earthquakes in a given period. To offset the figures given by Father Macelwane, I wish to state that in the twenty-four hours in which the great erup-

tion of the Taal Volcano in the Philippines occurred four hundred ninety eight distinct earthquake shocks were recorded by the Manila seismographs. Whether or not there is any connection or similarity between the swarms of earthquakes which occur prior to volcanic earthquakes and those who take place prior to tectonic earthquakes, doubtless we are not able to say, but it seems not at all impossible that the swarms recorded by Father Macelwane may indicate some stronger shocks yet to occur, and they at least warn us to be on our guard.

Remarks were also made by Messrs. Willis, Townley, and Tolman.

GEOLOGY AND PHYSIOGRAPHY OF THE PERUVIAN CORDILLERA IN THE DEPARTMENTS OF JUNIN AND LIMA

BY D. H. MC LAUGHLIN

(*Abstract*)

The area under discussion lies to the east of the city of Lima and includes the high country between the mining districts of Cerro de Pasco and Huancavelica. The summary of features of regional nature that is presented is based on the work of the Geological Department of the Cerro de Pasco Copper Corporation.

The dominant rocks of the section are Mesozoic limestones and sandstone. They are underlain by somewhat metamorphosed Paleozoic sediments and overlain unconformably by a thick formation of red shale and sandstone with conglomerates that are probably of Tertiary age. Volcanic deposits (mostly pyroclastic) occur between the Paleozoic sediments and the lowest Mesozoic limestone and again at the top of the later red beds. All are intruded by numerous small stocks and related masses, generally porphyries, ranging from diorite to quartz monzonite and trachyte in composition. Important periods of deformation occurred at the close of the Cretaceous and again after the deposition of the Tertiary sediments and related volcanic formations.

The modern Andes were formed by the warping uplift of a region of mild relief that had been formed by long-continued erosion following the last intense deformation of the Tertiary. The uplift took place in three or more stages and was in places accompanied by block-faulting. The old topography is practically obliterated by the steep streams of the Pacific side, but still exists in broad areas between the deep canyons of the eastern rivers of the central highlands. Intense glaciation, formerly extending to altitudes as low as 12,000 feet, is responsible for the present details of the topography of the summit regions.

Presented extemporaneously. Illustrated with lantern slides.

Discussion

Mr. Warren D. Smith: In looking at some of the very admirable pictures which Mr. McLaughlin has thrown on the screen, I was very strongly reminded of some landscapes in the highlands of Luzon. We have those same high level plateaus, cut off by very deep V-shaped gorges. Although the relief in the Philippines is not on as great a scale as it is in Peru, it is relatively as

great. I wish to call to the attention of the younger members of the Society who may not have seen Doctor Willis' early references to the subject of the unity of the Pacific, that here we have a striking bit of evidence in support of his ideas, and I am firmly convinced that the major physiographic features in the Philippines can be correlated with those in the high Andes, and that they are due to the same great movements in the Pacific region.

Also discussed briefly by Messrs. Robert Anderson and Willis.

PRELIMINARY REPORT ON THE GEOLOGY OF MOUNT DIABLO

BY BRUCE L. CLARK

(*Abstract*)

In the Mount Diablo Quadrangle is one of the most complete geologic sections in the Coast Ranges of California. Mount Diablo itself is composed of a typical Franciscan complex—that is, a mixture of sedimentary igneous and metamorphic rocks. The Cretaceous is represented by several thousand feet of shales and sandstones. The formations recognized are the Knoxville, the Pinoche, the Marino, and the Chico.

In the Tertiary section there are three groups of Eocene age—the Martinez, Meganos, and Tejon. The Oligocene is represented to the north side of Mount Diablo by several thousand feet of coarse clastics, while to the south of the mountain only a few hundred feet of deposits are referable to that age.

Two groups in the Miocene are recognized—the Monterey and the San Pablo. The Monterey is only poorly represented on the south side of the mountain by a few hundred feet, while it is absent in the section to the north of the mountain. The San Pablo group is divided into four local formations, the division of which is based upon the stratigraphy and the faunas.

The Pliocene is represented by a section of several thousand feet. Here there are four distinct formations to which local names are given.

Mount Diablo itself is brought up along a high angle thrust-fault, known as the Mount Diablo thrust. The mountain mass proper is a horst apparently bounded on all sides by high angle faults. The Mount Diablo thrust in places is intersected by a low angle thrust known as the Clayton thrust. The Clayton thrust extends from the northwest corner of the Mount Diablo sheet down toward the southeast edge, on to the Byron sheet. The Clayton thrust seems to have resulted from the Appalachian or Alpine structure—that is, originally an anticline overturned and thrust from the northeast to the southwest. The angle of the thrust varies; in the vicinity of the town of Clayton it averages about 6 to 7 degrees in dip to the north, while to the south and east of Mount Diablo it has an average dip of about 11 degrees. The Miocene and Pliocene sediments to the west of Mount Diablo are very highly folded and faulted between the Mount Diablo thrust to the east and the high angle thrust known as the Calaveras thrust, which is along the west side of the San Ramon Valley. There is very good evidence to show that compression and folding were contemporaneous, at least in part with these two thrusts and with the large cross-faults which cut through the Pliocene and along the west side of Mount Diablo. In places the Pliocene beds are overturned

towards the south and in other localities the Miocene beds are overturned toward the north.

Presented extemporaneously. Illustrated with map and diagrams. Discussed by Doctor Willis.

AN APPARENT-DIP PROTRACTOR

BY W. S. TANGIER SMITH

(*Abstract*)

This paper describes and figures a new type of apparent-dip protractor, by means of which the actual angle of apparent dip, rather than its numerical value, may be obtained when the true dip and direction angle are known.

The protractor is in quadrant form, with a rotating arm. When the arm is set so as to intersect lines on the face of the protractor corresponding to given values for true dip and direction angle, the angle formed between the rotating arm and the base of the protractor is the required angle of apparent dip, which may then be platted directly.

Presented extemporaneously.

KEMPITE, A NEW MANGANESE MINERAL FROM SANTA CLARA COUNTY, CALIFORNIA

BY AUSTIN F. ROGERS

(*Abstract*)

A huge boulder of manganese ore occurring in Alum Rock Park near San Jose, and locally known as the "Alum Rock Meteor," contains a new hydrous manganese oxychloride mineral, which has been named *kempite* in honor of Prof. J. F. Kemp, of Columbia University. The associated minerals are tephroite, hausmannite, rhodochrosite, barite, pyrochroite, ganophyllite, alabandite, and psilomelane.

Kempite is found in scattered specks and occasionally in small orthorhombic crystals. The color is emerald green and the chemical formula is $Mn\,Cl_2.\,3\,Mn\,O_2.\,3\,H_2O$.

Presented extemporaneously.

DIATOM THEORY OF ORIGIN OF PETROLEUM IN CALIFORNIA

BY JUN-ICHI TAKAHASHI

(*Abstract*)

The possibility and probability of diatoms as the origin of the petroleum deposits in general, and especially in California, were discussed. The conclusions are based on the results of chemical and microscopical studies of various diatomaceous deposits, both recent and geologic.

Read from manuscript.

DISCUSSION

Mr. DALLAS HANNA: The diatomanous origin of California asphalt oil has been generally admitted for many years, due to the close association of deposits of these organisms and the oils; but an analysis of actual diatom oil, made at the instance of Dr. Albert Mann, showed that in composition it differed greatly from crude petroleum. The presence of large numbers of other forms of life in the diatomaceous shales, more properly termed organic shales, has led conservative investigators to attach a little less importance to the diatoms. One of the most important facts for consideration in the problem is the presence of very large oil pools several thousand feet vertically above the organic shale; another feature is the presence of asphalt oils elsewhere in the world, sometimes in formations laid down long before diatoms appeared on earth.

Mr. WARREN D. SMITH: I am very much interested in the paper by Mr. Takahashi, and whether or not diatoms have given rise to the petroleum in California. I should like to note that in the petroliferous shales in the Philippines I have never found any *diatoms*. The only microscopic forms which seemed to be abundant in these shales were *globigerinas*.

Mr. ROBERT ANDERSON: The almost invariable occurrence of the oils in California in close conjunction with organic shale deposits of various ages leaves little room for doubt that these shales are the mother rock of these oils. The geologists of the Survey had expressly referred to them as "organic" rather than merely "diatomaceous" shales, so as to give recognition to the quantity of foraminiferal as well as other organic remains occurring therein in addition to the diatoms. The minute shell-inclosed organisms, both plant and animal, were favored as the source of oil, owing to the likelihood of more rapid decomposition and destruction of the protoplasm of the larger organisms.

Mr. Takahashi's paper was also briefly discussed by Mr. Tolman.

CRYSTAL SYMMETRY

BY AUSTIN F. ROGERS

(*Abstract*)

The application of the mathematical theory of groups to the problem of crystal symmetry proves that the true elements of symmetry are the following: plane of symmetry (P); center of symmetry, (C); axes of 2-, 3-, 4-, and 6-fold symmetry, (A_2), (A_3), (A_4), (A_6); composite planes and axes of 4- and 6-fold symmetry, ($\widehat{A_4P}$), ($\widehat{A_6P}$), and composite center and axis of 6-fold symmetry, ($\widehat{CA_6}$).

Presented extemporaneously. Illustrated with lantern slides.

DISCUSSION

Mr. MACLEWANE: Professor Rogers' paper contains very interesting developments of the application of Lie group theory to crystal structure. It is

becoming more and more necessary to consider the mathematical theory. Wyckoff brought out this necessity very clearly in his article on "Existing crystal structure data," in the Journal of the Franklin Institute last year (Feb., March, and April, 1923). He insisted that the data obtained from traditional crystallography and from the three methods of crystal analysis by X-Ray reflections could only be considered final when tested for further possibilities by means of the mathematical theory of groups.

MINERALIZATION IN THE RANDSBURG QUADRANGLE, CALIFORNIA

BY CARLTON D. HULIN

(*Abstract*)

All of the economically valuable mineralization in the quadrangle, which includes deposits of gold, silver, and tungsten ores, is of epithermal origin and of early Upper Miocene age. The formation of many of the deposits has been directly controlled by structural conditions.

Presented from notes.

RELATIONS BETWEEN BATHOLITHS AND SCHISTOSITY

BY ELIOT BLACKWELDER AND ELMER R. BADDLEY

(*Abstract*)

Current writings on geology indicate much difference of opinion and considerable misunderstanding of the relations between batholiths and the schistose structure or secondary cleavage of the country rocks, and particularly of the causation of such structures.

Out of nearly one hundred examples, the reports of which were investigated by the writers, about sixty were described with sufficient clearness of detail that they could be classified with reasonable confidence. Three distinct groups are evident.

In the greatest number of cases (67 per cent), the batholithic contact cuts across preexisting schistosity and other structures in various directions. Locally, magmatic emanations have penetrated along the cleavage planes, and for short distances the main contact follows such planes of weakness. In many cases, however, the contact metamorphism around the batholith has more or less completely obliterated the cleavage and other structures of the country rock. The result in such instances is an aureole consisting of massive amphibolite or hornfels. Excellent examples of these relations are found around the batholiths in the Sierra Nevada of California, and Marysville batholith of Montana, as well as others in Cornwall, the Rainy Lake District of Canada, and many places in Europe.

In about 10 per cent of the well-defined cases, the rocks surrounding the batholith exhibit schistosity parallel to the periphery of the intrusion. Van Hise has described this condition in the Black Hills of South Dakota, and other examples are given by Daly from the Selkirk Range of southwestern Canada, and by Spurr from Saskatchewan Province. The evidence indicates that the marginal rock had recrystallized under conditions of intense compression radiating out from the batholith.

There is another group of batholiths, represented by about 22 per cent of those here considered, in which the lenticular form of the intrusive mass, the mashed and granulated condition of the granite, and the elongation of all adjacent structures in the general direction of the regional cleavage indicate that both the internal structure of the intrusive rock, its form, and the cleavage of the country rocks have been caused by regional deformation, in which the intrusive and the older rocks have been intensely compressed together. This group is apparently illustrated by many of the batholiths in the southern Appalachian Mountains, as well as by those described by Lawson from the Rainy Lake District of Ontario and by Cushing from the northwest side of the Adirondack Mountains of New York.

It requires close and critical observations in the field to discriminate these three types.

There is probably significance in the fact that only 10 per cent of the batholiths investigated appeared to have induced peripheral schistosity, whereas more than two-thirds had merely cut across preexisting structures or had obliterated them. We suspect that there may be a relation to depth, and that the cross-cutting relation is characteristic of the more superficial parts of a batholith and especially of those that approach nearer to the surface, while at very great depth the marginal rocks become plastic and flow, making contorted gneisses. At intermediate depths and pressures the peripheral schistosity may be developed. Lastly, regardless of the original relations of the country rock and the intrusion, any region may subsequently be involved in great regional compression during a mountain-building epoch. The intrusive bodies may then be squeezed into lenses, while the country rock is converted into schists with cleavage parallel to such elongation.

Presented from notes. Discussed by Messrs. Rogers and Tolman.

ANNUAL DINNER

The annual dinner, with an attendance of twenty-three, was given under the auspices of the Le Conte Club, at the Stanford Union.

Register of the Stanford Meeting, 1924

FELLOWS

Robert Anderson
Eliot Blackwelder
John P. Buwalda
Bruce L. Clark
James M. Hill
Donald H. McLaughlin
Austin F. Rogers
Warren D. Smith
W. S. Tangier Smith
J. A. Taff
H. W. Turner
Bailey Willis

GUESTS

Elmer P. Baddley
Guy N. Bjorge
Fred Buss
C. A. Buttram
Perry Byerly, Jr.
Leslie M. Clark
C. H. Clickmay
H. L. Driver
Anthony Folger
E. L. Furlong
G. Dallas Hanna
George L. Green
Stanley C. Herold
Leo G. Hertlein
Harold W. Hoots
C. D. Hulin
Oliver W. Johnson
James B. Macelwane
Asa A. L. Mathews
William M. Nicholls
Mrs. Oldroyd
R. W. Pike
D. L. Powers
H. G. Schenck
J. P. Smith
L. L. Stewart
Chester Stock
Jun-ichi Takahashi
C. F. Tolman
G. H. Westby
C. H. White
E. V. Winterer
W. C. Wrather
W. D. Williamson

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 36, PP. 211-240 MARCH 30, 1925
PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

PROCEEDINGS OF THE SIXTEENTH ANNUAL MEETING OF THE PALEONTOLOGICAL SOCIETY, HELD AT ITHACA, NEW YORK, DECEMBER 29-31, 1924.

R. S. BASSLER, *Secretary*

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Session of Monday, December 29

PRESIDENTIAL ADDRESS

Wednesday morning at 9 o'clock the members met in Baker Laboratory with the Geological Society of America in general session of all the affiliated societies. At 12.15 p. m., in joint session, the presidential address of the retiring President of the Paleontological Society, E. W. Berry, was delivered, the subject being "On correlation." The meeting then adjourned until 2 p. m.

Monday afternoon at 2 p. m. President Berry called the sixteenth annual meeting of the Society to order in Baker Laboratory and requested the report of the Council as the first matter of business.

REPORT OF THE COUNCIL

To the Paleontological Society, in sixteenth annual meeting assembled:

A résumé of the Council's administration of the Society's business for 1924 is presented in the following report of the Secretary and Treasurer. The Council has held its usual two meetings and has transacted other business during the course of the year by correspondence.

Secretary's Report

To the Council of the Paleontological Society:

The Secretary's report for the year ending December 28, 1924, is as follows:

Meetings.—The proceedings of the fifteenth annual meeting, held at Washington, D. C., December 27-29, 1923, have been printed in volume 35, number 1, of the Bulletin of the Geological Society of America, pages 169 to 200. The Council's proposed nomination for officers for 1925, with announcement of the next meeting place at Ithaca, New York, as the guest of Cornell University, was mailed to the members on March 1, 1924.

Membership.—During the past year the Society has lost one of its members by death, Mr. Edward J. Whittaker, of the Geological Survey of Canada, who by a most unfortunate accident lost his life on September 14, 1924. One member has resigned. Eleven new members have just been elected. Three nominations await action at the present meeting and three fellows of the Geological Society of America have requested membership. Three of our members have been elected to fellowship in the Geological Society of America this year. The result of these various changes leaves a total number of members of 255 at the close of 1924.

Publications.—The publications of the Society for the year consist of the Proceedings, the presidential address, and the ten articles composing the symposium held last meeting, all appearing in the Bulletin of the Geological Society of America.

Treasurer's Report

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending December 26, 1924:

RECEIPTS

Cash on hand December 22, 1923		$930.61	
Membership fees		315.00	
Interest, Connecticut Savings Bank		34.55	
			$1,280.16

EXPENDITURES

Secretary's office:			
Secretary's allowance (A)	$100.00		
Clerical aid (B)	25.00		
Office expenses (C)	64.22		
		$189.22	
Treasurer's office:			
Treasurer's allowance (D)	$25.00		
Stationery (E)	11.55		
		36.55	
Pacific Coast Section:			
Printing (F)	$6.00		
Postage (F)	2.00		
		8.00	
Geological Society of America:			
Printing programs, etcetera (G)	$20.50		
Reprints from Bulletin of the Geological Society of America, volume 34 (H)	20.95		
Reprints from Bulletin of the Geological Society of America, volume 35, number 2 (I)	4.63		
		46.08	
Returned membership check (J)		3.00	
			282.85
Balance on hand December 26, 1924			$997.31
Net increase in funds			66.70
Outstanding dues (3 for 1923, 12 for 1924)			45.00

Respectfully submitted,
(Signed) CARL O. DUNBAR,
Treasurer.

NEW HAVEN, CONNECTICUT, *December* 26, 1924.

APPOINTMENT OF AUDITING COMMITTEE

President Berry appointed F. B. Loomis and W. J. Sinclair to audit the accounts of the Treasurer.

ELECTION OF OFFICERS AND MEMBERS

The Secretary then presented the results of the ballots for the election of officers for 1925 and new members.

OFFICERS FOR 1925

President:

R. S. LULL, New Haven, Conn.

First Vice-President:

T. E. SAVAGE, Urbana, Ill.

Second Vice-President:

E. C. CASE, Ann Arbor, Mich.

Third Vice-President:

CHARLES BUTTS, Washington, D. C.

Secretary:

R. S. BASSLER, Washington, D. C.

Treasurer:

CARL O. DUNBAR, New Haven, Conn.

Editor:

WALTER GRANGER, New York City

NEW MEMBERS FOR 1925

WILLIAM S. DYER, 70 Colbeck Street, Toronto, Ontario.
LEOPOLD A. FAUSTINO, Bureau of Science, Manila, Philippine Islands.
FRED C. HERPICH, Peabody Museum, Yale University, New Haven, Connecticut.
JOHN E. HOFFMEISTER, University of Rochester, Rochester, New York.
LAURA LEE LANE, 1105-1106 State National Bank Building, Houston, Texas.
L. ALFRED MANNHARDT, New York University, New York City.
MARIO SANCHEZ ROIG, Cerro 827, Havana, Cuba.
GEORGE G. SIMPSON, Peabody Museum, Yale University, New Haven, Connecticut.
WALTER R. SMITH, United States Geological Survey, Washington, D. C.
EDMUND M. SPIEKER, Department of Geology, Ohio State University, Columbus, Ohio.
HORACE ELMER WOOD, II, Columbia University, New York City.

The following three nominations, approved by the Council, but received too late for the printed ballot, were then presented to the Society for action:

I. ALLEN KEYTE, Associate Professor of Geology, Colorado College, Colorado Springs, Colorado. B. S., University of Missouri. Student of invertebrate paleontology. Proposed by R. S. Bassler and E. O. Ulrich.

DONALD KENNETH MACKAY, 1814 Grand Concourse, New York City. M. S., Princeton, 1924. Interested in invertebrate paleontology. Proposed by B. F. Howell and Richard M. Field.

ARTHUR C. MCFARLAN, Associate Professor of Geology, University of Kentucky, Lexington, Kentucky. Ph. D., University of Chicago, 1924. Interested in invertebrate paleontology. Proposed by E. O. Ulrich and R. S. Bassler.

Following a presentation of the qualifications of the above for membership it was voted that the By-Laws be suspended, and that the Secretary cast the vote of the Society for the election of these three new nominations.

The names of Prof. F. L. Whitney, University of Texas, Austin, Texas, and Dr. A. R. Crook, State Museum of Natural History, Springfield, Illinois, both Fellows of the Geological Society of America, were presented by the Council for election to our own Society. Mr. C. W. Gilmore, elected to fellowship in the Geological Society of America at the present meeting, was also considered in this connection. Following the rules of the Society, the three names were enrolled in our membership.

ELECTION OF CORRESPONDENT

President Berry then reported that the Council wished the Society to consider the election of the distinguished Austrian paleontologist, Prof. Othenio Abel, of the University of Vienna, as Correspondent. Professor Abel's work was briefly reviewed by the Secretary. Upon vote, Professor Abel was elected Correspondent unanimously.

With the conclusion of the business meeting President Berry called for the reading of the first paper of the program before the Society in general session.

PRESENTATION OF PAPERS

The first paper, dealing with the stratigraphy and the much-discussed question of the division line between the Devonian and Mississippian, was presented by the senior author. Discussion by Messrs. Berry, Bassler, and Branson.

RELATIONSHIP OF UPPER DEVONIAN AND LOWER MISSISSIPPIAN FAUNAS OF MISSOURI

BY E. B. BRANSON AND J. S. WILLIAMS

(*Abstract*)

The Snyder Creek shale of the middle part of the Upper Devonian contains the youngest Devonian fauna in Missouri. The oldest Mississippian faunas are contained in the Grassy Creek shale, Louisiana limestone and Sylamore

sandstone. The diastem between Devonian and Mississippian was relatively short, probably one-eighth to one-fifth the length of the Devonian. The fauna of the Grassy Creek shale consists mainly of lingulas and is not significant. The fauna of the Sylamore did not develop directly from the Snyder Creek fauna. Prominent new elements not present in the Snyder Creek are *Rhipidomella*, various types of *Productus* that could not have developed from the Snyder Creek forms, *Paraphorhynchus*, and other less important forms. None of the dominant Snyder Creek forms lived over. *Strophcodonta*, *Schizophoria*, *Atrypa*, striated spirifers, *Paracyclas*, *Schizodus*—all abundant in the Snyder Creek—do not occur in the Sylamore. The same forms are absent from the Louisiana limestone, and the dominant forms in the Louisiana, such as *Spirifer marionensis* Shumard, *Athyris hannibalensis* (Swallow), *Rhipidomella missouriensis* (Swallow), *Ambocœlia minuta* White, *Selenella pediculus* (Rowley), two species of *Chonetes*, and three species of crinoids could not have developed directly from the Snyder Creek species.

The conclusion is that the early Mississippian faunas of Missouri did not develop directly from the later Devonian faunas of Missouri.

A problematic Silurian fossil was then described and exhibited to the members by Professor Weller in an endeavor to learn its affinities. In the discussion that followed, by Messrs. Ruedemann, Foerste, and Parks, it was agreed that the specimens belonged to a new generic type of Conularida.

PROBLEMATIC FOSSIL FROM THE SILURIAN OF ILLINOIS

BY STUART WELLER

(Abstract)

There have been collected recently from the Silurian beds near Blue Island, Illinois, numerous examples of a peculiar fossil whose relationships are an enigma. The fossils themselves consist of carbonaceous material flattened out into a thin film. The organism which they represent was evidently a soft-bodied creature which lived in clusters, in some cases as many as ten individuals growing out from a base of attachment. The individuals themselves are flask-shaped bodies, usually about three inches in length when complete, the lower portion being about one-half inch wide, the upper portion tapering to a slender neck about one-eighth inch in width. The broader portion is covered with conspicuous transverse markings suggesting circular muscles in the living organism, the more slender portion being longitudinally wrinkled.

An exposition of Tertiary fossils and climate in the Great Plains and Great Basin, presented in the next paper, brought forth a discussion in which Messrs. Troxell, Berry, Matthew, and the author took part.

TERTIARY FORESTS AND CLIMATES IN THE GREAT BASIN AND GREAT PLAINS

BY RALPH W. CHANEY

(*Abstract*)

Fossil evidence in the northern Great Basin region indicates that this area was occupied by forests as late as the end of the Miocene. In the great plains there is no evidence indicating the presence of forests after the Eocene. The suggestion may be made that the Rocky Mountain uplift was responsible for the disappearance of the forests there during the early part of the Tertiary. The uplift of the Cascades during later Tertiary times had a similar effect upon the forests of the Great Basin in later Tertiary times.

The minute toothlike structures known as conodonts, much neglected by American paleontologists, formed the subject of the next paper, which was illustrated by lantern slides and specimens. Discussion by Messrs. Schuchert, Twenhofel, and Parks.

CLASSIFICATION AND STRATIGRAPHIC USE OF THE CONODONTS

BY R. S. BASSLER

(*Abstract*)

Conodonts, the microscopic fossil organisms resembling miniature sharks' teeth, are exceedingly abundant in certain Paleozoic formations, particularly black shales, which, on account of larger fossils, have often been in dispute as to their age and correlation. The published work upon these fossils is meager and sometimes of little value, because so often poorly illustrated and based upon incomplete specimens. Excellent series of conodonts have been accumulated in the United States National Museum collections by E. O. Ulrich and the writer during the past 25 years. The ever-increasing interest in the study of microscopic fossils for subsurface investigations has caused us to take up the present work of formulating a reasonable and, it is hoped, natural classification, so that future investigators can employ the conodonts to more advantage than has been done in the past. Details of this classification and descriptions of several faunas to illustrate the great value of conodonts in stratigraphic work will appear in a forthcoming paper. The classification is as follows:

I. Distacodidæ, new family. Consisting of a central tooth or main cusp without denticles. Includes *Distacodus* Hinde, *Acodus*, *Acontiodus*, *Drepanodus*, *Scolopodus*, *Oistodus*, and *Paltodus*, all of Pander.

II. Prioniodidæ, new family. Similar to the Distacodidæ, but a posterior denticulated extension is developed. Includes *Prioniodus* Pander, *Subprioniodus* Smith, *Beltodus* and *Cordylodus* Pander, and the new genus, *Ligonodina* (genotype *L. pectinata* new species, Upper Devonian of western New York), distinguished by the development of a series of sucker-like impressions on the downward extension of the main cusp.

III. Prioniodinidæ, new family. Similar to the Prioniodidæ, but the base of the tooth or bar is denticulated both forward and back. Includes *Cornuramia*, *Valentia* and *Pachysomia* Smith, *Lonchodus* and *Prionognathus* Pander, and the following new genera:

1. *Prioniodina*, new genus. Base of tooth more or less curved, crowned with numerous, subparallel, rounded, discrete denticles, one of which is considerably larger than the other. Genotype, *P. subcurvata*, new species. Upper Devonian of western New York.
2. *Euprioniodina*, new genus. Like *Prioniodina*, but major cusp much produced and anterior part of bar smaller, shorter, more or less sharply deflected, and carrying on its upper edge a series of closely arranged denticles. Genotype, *E. deflecta*, new species. Upper Devonian of western New York.
3. *Lonchodina*, new genus. Like *Euprioniodina*, but ends of bar more equal in length and the entire bar strongly bowed, especially as seen in profile of the base; denticles more irregular and farther separated. Genotype, *L. typicalis*, new species. Upper Devonian of western New York.
4. *Prioniodella*, new genus. Like *Prioniodina*, except that the denticles are subequal, no one being particularly larger than the others. Genotype, *P. normalis*, new species. Upper Devonian of western New York.
5. *Bryantodus*, new genus. Like *Prioniodina*, but denticles sharp-edged and their sides largely coalescent. Genotype, *B. typicus*, new species. Upper Devonian of western New York.
6. *Hibbardella*, new genus. Anterior and posterior ends equally developed, the tooth being bilaterally symmetrical and the main cusp erect and enormously developed. Genotype, *H. angulata* Hinde. Upper Devonian of western New York.
7. *Hindeodella*, new genus. Bar long and straight, bearing 6 to 8 small denticles in front of the strong, long, main denticle and a long series of small denticles, often alternating behind it. Genotype, *H. subtilis*, new species. Early Mississippian of Tennessee.
8. *Diplododella*, new genus. Bilaterally symmetrical as in *Hibbardella*, but denticles are fused and minutely bifurcated, the base is thicker and the main cusp smaller. Genotype, *D. bilateralis*, new species. Early Mississippian of Alabama.
9. *Palmatodella*, new genus. Like *Prioniodina*, except that bar is straighter, its anterior end longer and wider than the posterior, and bent at right angles to it, and all denticles much finer, sharply directed forward and for the most part fused. Genotype, *P. delicatula*, new species. Early Mississippian of Alabama.
10. *Synprioniodina*, new genus. Like *Palmatodella*, except that the downturned front is much smaller, bar thick, denticles not turning forward so sharply, and the main cusp proportionately very large. Genotype, *S. alternata*, new species. Lower Mississippian of Alabama.

IV. Polygnathidæ, new family. Plates with a high denticulated median or lateral crest, sometimes extending stalklike from one end. Includes

Polygnathus Hinde, *Gnathodus* Pander, *Panderodella* new genus, *Polygnathellus* new genus, and *Ctenognathus* Pander. In *Panderodella* (genotype, *P. truncata*, new species, Early Mississippian of central Tennessee) the summit of the pectinated crest is straight, crowned with small subequal denticles, highest at one end, declining towards the other, bowed, and rises abruptly from the convex edge of the expanded base, which is thus developed only on one side. *Polygnathellus*, new genus (Genotype, *P. typicalis*, new species, Upper Devonian of western New York), is similar to *Panderodella*, but the denticles are more irregular and longest in the middle part, the summit of the crest thus sloping towards each extremity.

The stratigraphy and paleontology of the Permian of West Virginia was then described by the next speaker, who presented his results in a detailed diagram. Discussion by R. S. Bassler.

CROSS-SECTION OF THE PERMIAN IN WEST VIRGINIA

BY JOHN L. TILTON

(*Abstract*)

The diagrams along the dip contrast the structure in the area of Permian strata with the structure across the State east. The diagrams along the strike illustrate the structure northeast-southwest through the Permian area and illustrate the location of fossils found. The section of the strata gives the sequence of the strata and also the horizons of fossils found. Progress is stated in the determination of the fossils. The paper will be published in full on completion of the study of the fossils.

A report of progress from Doctor Grabau as to his recent work on the stratigraphy of China was presented for the author by Doctor Ruedemann.

RECENT PROGRESS IN PALEOZOIC STRATIGRAPHY IN CHINA

BY A. W. GRABAU

(*Abstract*)

The discovery of graptolite faunas of Deepkill and Normanskill age in China is announced, as well as that of an Upper Cambrian fauna with *Clonograptus* and of a Silurian fauna of approximately Monroan age.

A stratigraphic paper dealing with the early Mississippian was next on the program. Presented by the author and illustrated by lantern slides. Discussion by Messrs. Weller and Schuchert.

EARLY MISSISSIPPIAN ROCKS OF NORTHERN TENNESSEE

BY R. S. BASSLER

(*Abstract*)

Former studies by the writer have shown that the usual sequence of early Mississippian formations in central Tennessee, namely, that of the early Kinderhookian—Chattanooga shale followed by the Keokuk—Fort Payne chert is different in the area just north of Nashville, due to the intercalation of the Upper Kinderhookian—Ridgetop shale and the Burlington—New Providence shale and limestone deposited in definite baylike areas headed toward the Nashville Dome. Field-work of 1925 in the Cumberland River district of the northeastern Highland Rim of this State shows another development of these same formations under similar circumstances. In this highly dissected area outcrops are so numerous that the intercalated formations can be traced from their old shorelines to their maximum development of several hundred feet each. As this is an area of numerous structural domes, the additional formations here developed are of increased interest in connection with the occurrence of oil.

A discussion of an interesting problem in the Cenozoic history of northern Texas was presented in the next paper, illustrated by diagrams and specimens. Discussed by Professor Loomis and other vertebrate paleontologists present.

BLANCO AND ASSOCIATED FORMATIONS OF NORTHERN TEXAS

BY W. D. MATTHEW

(*Abstract*)

The eastern escarpment of the Staked Plains in northern Texas is capped by late Tertiary and Pleistocene formations resting unconformably on Triassic and Permian. The Cenozoic thins out to the north and south, the principal exposures extending from Donley County in the north to Crosby County in the south. It is chiefly a fine-grained pinkish clay, varying to calcareous or arenaceous, usually with a basal conglomerate or sandstone layer. This formation was called the Panhandle by Gidley and referred to the Miocene, but is almost barren of fossils. Sandy and clayey lenses and strips traverse it and contain practically all the fossil faunas. Gidley interpreted these as canyons or valleys cut in the Panhandle formation, and distinguished three successive formations of this type—the Clarendon, Blanco, and Rock Creek—correlated by their fossil faunas as Upper Miocene, Middle Pliocene, and Lower Pleistocene. He considered these as wholly subsequent to the Panhandle. The work of the American Museum party showed that at some points the base of the Panhandle was of Lower Pleistocene age, and that, while the Rock Creek beds are wholly subsequent to the Panhandle, except, perhaps, for its capping layers, the Blanco appears to be interdigitated with the upper part of the Panhandle in Crosby County, and the Clarendon is interdigitated with

the lower part of what appear to be the Panhandle beds in Donley County. We therefore, while agreeing with Gidley that the fossiliferous lenses are stream valley deposits, regard them as largely contemporary with the Panhandle clay formation and not wholly subsequent; and we consider this formation as essentially a consolidated eolian loess, deposited on the plains surface under the same conditions that prevail today, except that the stream valleys were not cut so deep. Whether eolian or not, we are confident that it corresponds in origin to the banded clays of the White River and more or less similar formations of the Miocene.

All the fossils of the Staked Plains Tertiary come from the limited exposures of river valley deposits; the Panhandle beds, though extensively exposed, are barren of fossils.

Our party spent only a few days in the Paloduro and Yule canyon regions, finding in the Clarendon and Rock Creek beds the same faunas as described by Gidley, Lull, and Troxell, but no specimens worthy of especial notice. The Blanco exposures were more carefully prospected and a number of good finds made. The most important was the complete skeleton of the large horse described as *Equus simplicidens* by Cope and referred to *Pliohippus* by Gidley, but known hitherto only from a few teeth. It proves to be an intermediate genus, to which I have given the name *Plesippus*. A smaller horse, *Hipparion phlegon*, formerly known only from a few teeth, is represented by skull, jaws, limb bones, and complete feet; and there is a skeleton, probably almost complete, of a new camelid, jaws of mastodon, and various other fragmentary specimens of horses, camels, peccaries, *Megalonyx*, *Glyptodon*, etcetera.

The final paper of the afternoon session was delivered by the senior author and was discussed by Doctor Matthew.

OLIGOCENE SECTION IN BATTLE CREEK CANYON, WASHINGTON COUNTY, SOUTH DAKOTA

BY HORACE ELMER WOOD, 2ND, AND L. ALFRED MANNHARDT

(*Abstract*)

The "New York University Field Expedition in Vertebrate Paleontology, 1923," spent seven weeks in the South Dakota Bad Lands, collecting chiefly in Battle Creek Canyon. It was in the field from June 25 to August 13. The personnel consisted of Assistant Prof. L. Alfred Mannhardt (in charge) and Mr. Horace Elmer Wood, 2nd, both of the Biology Department of Washington Square College, New York University, and three volunteer assistants—Mr. Henry Seton, Mr. Herbert Hollander, and Mr. George Robinson.

The collecting was practically confined to the Oligocene, especially the "Turtle-Oreodon Zone" of the Oreodon beds.

The "Turtle-Oreodon Zone" fauna collected, as provisionally identified, agrees strikingly with that described by Sinclair (1924), not only in the forms represented, but even in such matters of proportion as the prevalence of *Hyænodon* over both dogs and cats. As the collection is worked up, further communications will probably follow.

We wish here to state our entire agreement with the stratigraphic observa-

tions and conclusions of Sinclair,[1] as well as with the stratigraphic part of Wanless' paper.[2]

The Oligocene section in Battle Creek Canyon, about six and a half miles from Wanless' nearest section (at the north end of Kuney Table), differed from it in several respects, although not more than might fairly be expected in a continental formation. It was carefully measured by Brunton level, height of eye, and a six-foot rule.

Wanless' terminology	Battle Creek Canyon section, top of Kuney Table, Oligocene, 403 feet.
Leptauchenia	Leptauchenia beds.
Pinkish, gray, ashy clays	Pinkish, gray clays, 168 feet; fossils very rare.
Oreodon, 215 feet	"Persistent white layer (ash?).
Upper Oreodon red clays, 61 feet	Oreodon beds, 172 feet.
Green sandy silts, 50 feet	Upper fossiliferous, reddish clays; fossils fairly common, 52 feet.
Upper nodular layer	Upper nodular layer.
Green and pink silts and clays 55 feet.	Upper barren, differential erosion marked; reddish clays and sandstones, 56 feet; fossils very rare.
Lower nodular zone or "Turtle-Oreodon zone," 46 feet	Lower fossiliferous, red clay, very fossiliferous, 22 feet 8 inches; upper 6 feet 5 inches very dark red. Lower barren, reddish clays and sandstones, 41 feet; fossils rare.
Algal limestone, 6 inches	Chert, 4 inches.
Titanotherium	Titanotherium beds, 63 feet 5 inches (up to 83 feet, estimated). Clays and sandstones, dominantly green. There was a widely distributed white band (perhaps ash), usually about five feet above the Pierre shale, but locally, due to depressions in the upper surface of the Pierre, as much as 25 feet. For about 2 feet on each side of this band fossils were unusually abundant.
Pierre shale	Pre-Pierre shale.

[1] The Turtle-Oreodon layer, or red layer, a contribution to the stratigraphy of the White River Oligocene. Proc. Am. Phil. Soc., vol. lx, no. 3, 1921. The faunas of the concretionary zones of the Oreodon beds, White River Oligocene. Proc. Am. Phil. Soc., vol. lxiii, no. 1, 1924.

[2] The stratigraphy of the White River beds of South Dakota. Proc. Am. Phil. Soc., vol. lxii, no. 4, 1923.

At 5.30 p. m. the Society adjourned to meet again at 8 p. m., with the Geological Society of America, to hear the address of the retiring President of that Society, Dr. Waldemar Lindgren, on "Metasomatism." At 9 p. m. the members attended the complimentary smoker, given in Prudence Risley Hall by Cornell University, to the Geological Society of America and its affiliated societies.

Session of Tuesday, December 30

No regular session of the Paleontological Society was scheduled for Tuesday morning, in order that the members could meet with the Geological Society of America in general session.

At 2 p. m. the Society met in Baker Laboratory, with President Berry in the chair. The first paper of the session was by President Berry and was entitled

ANCESTRY OF CERTAIN MONOTYPIC, DITYPIC, AND SMALL GENERA OF PLANTS

BY EDWARD W. BERRY

(*Abstract*)

There is much current interest, especially among botanists, regarding the theories of distribution propounded by Willis, commonly known as the Age and Area Hypothesis. The present paper presents the results of an examination of a number of plant genera whose geological history is fairly well known which show that they do not conform to the Willis hypothesis.

President Berry then presented a second paleobotanical paper of general interest, which brought forth a discussion from the vertebrate paleontologists present.

AGE AND ECOLOGICAL SIGNIFICANCE OF A MIDDLE EOCENE FLORA FROM THE WIND RIVER BASIN

BY EDWARD W. BERRY

(*Abstract*)

An account of a flora of Middle Eocene age collected in the Wind River Basin of Wyoming, with a discussion of its correlation and environmental significance.

A paper on vertebrate paleontology of general interest from both the stratigraphic and paleontologic standpoints was then presented by the author. Discussion by Messrs. Loomis, Berry, and Bassler.

FOSSIL MAMMAL FAUNAS OF FLORIDA

BY W. D. MATTHEW

(*Abstract*)

A visit to Florida last March enabled me to study the collections in the State Geological Survey collections at Tallahasse, various other local collections, and the principal localities where fossil mammals have been found.

The results confirm the excellent work of Sellards, except that his Miocene faunal zone appears to include two distinct zones—one in the body of the Alum Bluff formation, of Lower Miocene or Upper Oligocene age, the other in the fullers' earth member at the top, which was Middle Miocene.

The Hipparion fauna of the phosphate workings appears to be of Pliocene age, not Pleistocene, as claimed by Doctor Hay. The supposed element of Pleistocene species is an admixture due to circumstances readily understood when the field localities are examined.

A technical paper followed, but the subject-matter and the preparation exhibited by the author were of unusual interest. Discussed by Doctor Matthew.

BRAIN OF THE PHYTOSAURS

BY MAURICE G. MEHL

(*Abstract*)

An internal mold of the brain capsule of a slender-snouted phytosaur from the Trias of Arizona shows a brain exceptionally small, even for an ancient reptile.

The brain, as determined from the details of such a mold, indicates a much closer homology with that of certain existing fishes than with the reptilian brain as previously known.

An occurrence of Indian relics with vertebrate remains and the unusual methods of securing the specimens were then described, followed by a discussion in which many of the members took part. Illustrated by lantern slides.

NEW ANTILOCAPRID FROM THE POST-GLACIAL OF SASKATCHEWAN

BY W. A. PARKS

(*Abstract*)

Near Dundurn, about 20 miles south of Saskatoon, Saskatchewan, is a bog about 100 yards in diameter opening out on one side into a still larger swampy depression. In a few places springs come up through the muck of the bog. A section through the bog shows four feet of muck, six feet of sand, and a few inches of gravel lying on the clay substratum. In the gravel occur numerous arrowheads, shaped flints, and other articles of Indian workmanship, and

with these are numerous fragments of bone, teeth, and other parts of animals. Most of the remains are referable to *Bison*, but three lower molars were found that seem to represent a new genus and species of the *Antilocapridæ*.

A paper describing new dinosaurs of special interest from the evolutionary standpoint was then presented, illustrated by lantern slides.

NEW GENUS AND SPECIES OF HORNED DINOSAUR FROM THE CRETACEOUS OF ALBERTA

BY W. A. PARKS

(*Abstract*)

The Belly River and Edmonton beds of Alberta have yielded a remarkable series of horned dinosaurs which has added much to the knowledge of the evolution of the group. The solid-frilled form, *Triceratops*, has not yet been found, but the new genus has a fontanelle so small that it approaches more closely to *Triceratops* than any other species; it is an interesting link connecting *Triceratops* with the open-frilled forms.

The next speaker gave the results of his detailed studies in tooth development of the Artiodactyls in a paper amply illustrated, which when published will be of utmost value to students of this large group of mammals. Discussion by various members of the Society.

ORIGIN AND DEVELOPMENT OF THE ARTIODACTYL DENTITION

BY F. B. LOOMIS

(*Abstract*)

The so-called cusps of the premolar and molar teeth of artiodactyls have developed as ridges, or crests, and cingula, incident to the elongation and widening of simple primitive teeth. The shortening of upper premolar 4 has taken place in different ways in the different phyla, and offers a way of distinguishing one phylum from another. The same is true of the fourth premolar of the lower dentition. This established, the paper will take up the several phyla of artiodactyls, oreodons, camels, deer, antelopes, etcetera, and show how the later members of the phylum have still further modified the fundamental patterns. An attempt will be made to develop a phylogeny for the whole group.

The subject of mechanics in the crocodile skeleton was then presented, with illustration by specimens and drawings.

MECHANICS OF THE CROCODILE SKELETON

BY EDWARD L. TROXELL

A second paper on the phytosaurs followed, illustrated by charts.

DEVELOPMENT OF A SECONDARY PALATE IN THE PHYTOSAURIA

BY MAURICE G. MEHL

(*Abstract*)

A series of phytosaur skulls has been selected to show the development of a secondary palate. At one extreme is found such faunas as *Angistorhinus grandis*, in which there is a simple narial vault without constriction at the level of the palate plane. At the other end of the series is a new genus from Arizona, in which the secondary palate is complete and the air passage leads considerably back of the nares. *Machæroprosopus andersoni* is an intermediate stage, in which the lateral constriction at the base of the narial vault was probably completed by membraneous extensions from either side.

Contrary to what has been supposed, the alveolar ridges play no part in the development of the "false palate."

A new fauna and stratigraphic horizon of Eocene age in the Pacific States was discussed in the following paper:

DOMENGINE HORIZON (MIDDLE EOCENE), A NEWLY RECOGNIZED DIVISION IN THE EOCENE OF CALIFORNIA

BY BRUCE L. CLARK AND RALPH B. STEWART

(*Abstract*)

A new fauna is recognized in the Middle Eocene of California, in beds stratigraphically below those containing a Tejon fauna and above those of Meganos age. Beds containing this fauna occur at the south end of the San Joaquin Valley unconformably below those containing the fauna of the typical Tejon (Upper Eocene). A part of this horizon was formerly considered by the senior writer to be Meganos, but in one locality it was called Tejon. A number of species are common to the Meganos and likewise to the Tejon, but, taken as a whole, the fauna is distinctive. This fauna has been recognized in various localities from Washington to southern California.

Professor Branson then presented for the author an account of a new and unusual crinoid fauna.

PENNSYLVANIAN CRINOIDS FROM WESTERN COLORADO

BY I. A. KEYTE

(*Abstract*)

During the summers of 1923 and 1924 the writer collected about one hundred Pennsylvanian crinoids from the north bank of the Colorado River, near McCoy, Colorado. Nine or ten genera are represented in the collection. Many of the species are undescribed.

The genus *Onychocrinus* is represented by five specimens, two of which are armed specimens. Other genera represented are: *Delocrinus, Hydreionocrinus, Erisocrinus, Eupachycrinus, Ulocrinus, Cromyocrinus, Scaphiocrinus,* and *Graphiocrinus.*

The curious depauperate fauna at the base of the Richmond (Maquoketa) shale formed the subject of the next paper. Discussion by Messrs. Clark and Bassler.

DEPAUPERATE FAUNA OF THE MAQUOKETA

BY HARRY S. LADD

(*Abstract*)

The base of the Maquoketa shale in the upper Mississippi basin seems to be characterized everywhere by a thin fossiliferous bed bearing a unique fauna, made up almost entirely of unusually small individuals and hence called a *depauperate fauna*. This fauna has been studied from fourteen localities—from Winneshiek County, in northeast Iowa, to Calhoun County, in southeast Illinois, including one locality in Pike County, Missouri. In addition, it has been reported from Sainte Genevieve County, in southeast Missouri, and from southwest Wisconsin.

The lithology and thickness of the zone show considerable variation, but the fauna is remarkably constant. The species show much variation in relative abundance. Certain ones are unusually abundant in small areas and practically absent elsewhere, while certain others are widespread and form excellent index fossils. The fauna is chiefly molluscan, but almost all the other important groups of invertebrates are represented and will probably total close to fifty species. It is hoped that additional studies which are now being carried on will add much to what is now known of this horizon. Its persistence and other unusual features make it a valuable horizon for all stratigraphic work.

The final paper of the program was presented for the author by Doctor Reeds.

PROTOCERATOPS, A PRIMITIVE CERATOPSIAN FROM THE LOWER CRETACEOUS OF MONGOLIA

BY C. C. MOOK

The Society then adjourned until 7 o'clock, when the members met in Prudence Risley Hall, with the Geological Society of America and affiliated societies, for the annual dinner.

In the absence of the authors, the following papers were then given by title:

MECHANICAL FACTORS IN THE EVOLUTION OF THE TETRABRANCHIATE CEPHALOPODS

BY PERCY E. RAYMOND

(*Abstract*)

The dominant factor in the life of a tetrabranchiate cephalopod, aside from its aqueous medium, was the gas which accumulated in its deserted chambers.

The buoyancy which it supplied induced swimming or floating, rather than crawling habits, and usually, where not counteracted by internal calcareous secretions, resulted in coiled shells. Coiling was not primarily an attribute of the animal, but was the result of the environment. That cephalopods of successively later periods began to coil at earlier and earlier stages in the ontogeny appears to show that the "acquired characteristic" was eventually inherited.

The complex sutures of the ammonite remain a puzzle. Efforts to explain them have centered about an explanation of their possible use to the animal, which is putting the effect before the cause. The ammonite was a buoyant animal, probably pelagic. The dominant feature of the ammonitic suture is rhythm. Waves are rhythmic. Is there possibly a connection?

PLEISTOCENE FORAMINIFERA FROM THE PALOS VERDES HILLS OF CALIFORNIA

BY J. J. GALLOWAY AND S. G. WISSLER

OLENELLUS WITH ANTENNULES

BY CARL O. DUNBAR

(*Abstract*)

Among the many fine specimens of the Noah L. Getz collection of Lower Cambrian fossils recently acquired by Yale is a large and very perfect Olenellus with both antennules clearly preserved.

The character of these delicate tactile organs has been known in but four genera of the trilobites, and this adds a fifth genus and a fourth family to the list. Interest in this specimen is augmented by the fact that it is older than the others and is the first Lower Cambrian trilobite to reveal any of its segmented appendages.

AMERICAN TRICONODONTS

BY GEORGE G. SIMPSON

(*Abstract*)

The triconodonts are a group of Jurassic (Stonesfield, Purbeck, Morrison) mammals. A study of the available American material, most of which is in the Yale Peabody Museum, has been undertaken.

Marsh's genus *Priacodon* is accepted as valid, and his reference of certain remains to the genus *Triconodon* is also defended. A species referred by him to *Tinodon* (*T. robustus*) is removed to the genus *Priacodon*.

Much undescribed upper jaw material has been prepared and studied. At least four species are represented by fairly complete molar dentitions. The pre- and sub-orbital regions of the skull, as also the jugal and the palate, are made known.

The true triconodonts are not considered as ancestral to any other known forms, but as a separate phyletic series, quite possibly distinct even in its pro-mammalian ancestry, becoming totally extinct at the close of Jurassic time.

RECONNAISSANCE OF PART OF THE SANTA FE FORMATION

BY GEORGE G. SIMPSON

(*Abstract*)

Ten weeks of the summer of 1924 were spent collecting vertebrate fossils from this formation for the American Museum of Natural History. The area treated extends for about forty miles north of Santa Fe and is chiefly in the broad Espanola Valley of the Rio Grande River. The beds from which fossils were collected are described in some detail and their relations to the other rocks of the region considered. It is concluded that there are two types of deposits—coarser stream channel beds and finer floodplain beds. The latter, in part fluviatile and in part eolian, are the more fossiliferous. The sediments were derived chiefly from the Santa Fe Range to the east. Sedimentation was complete before the inauguration of the volcanic era, the results of which are now so prominent a part of the geology of the region.

Minutes of the Meeting of the Pacific Coast Section of the Paleontological Society

The session of the Pacific Coast Branch for 1924 occurred at the Department of Geology, Stanford University, April 5, 1924. The meeting was called to order by the President, Dr. Ralph W. Chaney. In the absence of the Secretary, Dr. Chester Stock, Mr. H. G. Schenck was appointed Acting Secretary. The President announced that he would appoint a nominating committee for officers for the coming year. The program was then presented as follows:

PRESENTATION OF PAPERS

AMMONITES FROM THE CRETACEOUS OF COLOMBIA

BY FRANK M. ANDERSON

Read by title.

BIDAHOCHI PLEISTOCENE DEPOSITS OF THE CORNFIELDS—HOPI VOLCANIC BUTTES FIELD, ARIZONA

BY ALBERT B. REAGAN

Read by title.

EOCENE MOLLUSCAN GENERA NEW TO THE TERTIARY OF CALIFORNIA

BY RALPH B. STEWART

PREMOLAR AND MOLAR DENTITION OF ARTIODACTYLS

BY F. B. LOOMIS

MAN IN THE LATE PLEISTOCENE OF FLORIDA

BY F. B. LOOMIS

CORRELATION OF THE PHILIPPINE TERTIARY WITH ASIA, EUROPE, AND AMERICA

BY LEOPOLD A. FAUSTINO IN COLLABORATION WITH DALE D. SPARKS

MOUNTED SKELETON OF THE PLEISTOCENE HORSE OF RANCHO LA BREA

BY CHESTER STOCK AND EUSTACE L. FURLONG

Read by E. L. Furlong.

AGE OF THE EUGENE FORMATION, OREGON

BY HUBERT G. SCHENCK

STUDY OF THE MOLLUSCAN FAMILY CASSIDIDÆ

BY HUBERT G. SCHENCK

RELATION OF THE PERMIAN FOSSIL PLANTS OF THE RUSSIAN FAR EAST TO THE FLORAS OF THIS AGE FROM OTHER PARTS OF THE WORLD

BY M. K. ELIASHEVICH

TWO CONIFERS FROM THE TERTIARY OF OREGON

BY RALPH W. CHANEY

RECENT AND FOSSIL SPECIES ON BOTH SIDES OF THE ARCTIC

BY MRS. IDA OLDROYD

A TRIASSIC FAUNA FROM UTAH

BY A. L. MATHEWS

DISCOVERY OF A LOWER JURASSIC FAUNA IN THE ROCKY MOUNTAINS OF CANADA

BY COLIN CRICKMAY

STRATIGRAPHIC AND FAUNAL EVIDENCE FOR EOCENE HORIZONS IN CALIFORNIA

BY BRUCE L. CLARK

Register of the Ithaca Meeting, 1924

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WOOD, HORACE ELMER, II, Columbia University, New York City.

CORRESPONDENTS DECEASED

KOKEN, E. Died November 24, 1912.
NATHORST, Dr. A. C. Died Jan. 20, 1921.
WOODWARD, Dr. H. Died Sept. 6, 1921.

MEMBERS DECEASED

BARRELL, JOSEPH. Died May 4, 1919.
BILLINGS, W. R. Died March 1, 1920.
BOSTWICK, THOMAS A. Died April, 1923.
CALVIN, SAMUEL. Died April 17, 1911.
CLARK, WM. B. Died July 27, 1917.
CROZEL, GEORGE. Died October, 1921.
DERBY, ORVILLE A. Died Nov. 27, 1915.
DONEGHY, JOHN T. Died June 29, 1921.
EASTMAN, CHAS. R. Died Sept. 27, 1918.
FONTAINE, WM. M. Died April 30, 1913.
GILL, THEODORE N. Died Sept. 25, 1914.
GORDON, ROBERT H. Died May 10, 1910.
HAMLIN, HOMER. Died July, 1920.
HARPER, GEORGE W. Died Aug. 19, 1918.
HAWVER, J. C. Died May 15, 1914.
LAMBE, L. M. Died March 12, 1919.
LYON, VICTOR W. Died Aug. 17, 1919.
MATTHEW, GEO. F. Died April 17, 1923.
MOODY, W. L. Died October 9, 1920.
PROSSER, C. S. Died Sept. 11, 1916.
SEELY, HENRY M. Died May 4, 1917.
TELLER, EDGAR E. Died July 19, 1923.
VOGDES, ANTHONY W. Died Feb. 8, 1923.
WARING, CLARENCE A. Died Nov. 4, 1918.
WILLIAMS, HENRY S. Died July 31, 1918.
WILLISTON, S. W. Died Aug. 30, 1918.
WHITTAKER, EDW. J. Died Sept. 14, 1924.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 36, PP. 241-246 MARCH 30, 1925

PROCEEDINGS OF THE FIFTH ANNUAL MEETING OF THE MINERALOGICAL SOCIETY OF AMERICA, HELD AT CORNELL UNIVERSITY, ITHACA, NEW YORK, DECEMBER 31, 1924.

FRANK R. VAN HORN, *Secretary*

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SESSION OF WEDNESDAY MORNING, DECEMBER 31

The Mineralogical Society of America held its fifth annual meeting at Cornell University, Ithaca, New York, in conjunction with the Geological Society of America.

At 9 a. m. the meeting was called to order by President Henry S. Washington in the geological lecture room of McGraw Hall.

On motion of the Secretary, the reading of the minutes of the last annual meeting was dispensed with, in view of the fact that they have been printed on pages 56-69 of volume 9, number 3, of the American Mineralogist.

ELECTION OF OFFICERS AND FELLOWS

The Secretary announced that 128 ballots had been cast for the officers and Fellows, as nominated by the Council. All 128 ballots for officers were in the affirmative. For Fellows, there were 57 in the affirmative and one in the negative for certain men. All officers and Fellows as

nominated were declared elected. The officers for 1925 are the following:

President, ARTHUR S. EAKLE

University of California, Berkeley, Calif.

Vice-President, H. P. WHITLOCK

American Museum of Natural History, New York City

Secretary, FRANK R. VAN HORN

Case School of Applied Science, Cleveland, Ohio

Treasurer, ALEXANDER H. PHILLIPS

Princeton University, Princeton, N. J.

Editor, WALTER F. HUNT

University of Michigan, Ann Arbor, Mich.

Councilor, WILLIAM F. FOSHAG

United States National Museum, Washington, D. C.

The list of Fellows elected follows:

WILBUR S. BURBANK, United States Geological Survey, Washington, D. C.
LAZARD CAHN, Colorado Springs, Colorado.
FRANCIS D. DODGE, Brooklyn, New York.
ERNEST E. FAIRBANKS, United States Bureau of Mines, Reno, Nevada.
JAMES G. MANCHESTER, New York City.
J. J. RUNNER, Iowa State University, Iowa City, Iowa.
OTTO VON SCHLICHTEN, University of Cincinnati, Cincinnati, Ohio.
ALFRED WANDKE, Guanajuato, Mexico.
SAMUEL WEIDMAN, University of Oklahoma, Norman, Oklahoma.
EDWARD WIGGLESWORTH, Boston Society of Natural History, Boston, Massachusetts.
JOSEPH P. WINTRINGHAM, Brooklyn, New York.

REPORT OF THE SECRETARY

The Secretary reports that the roll of the Society now comprises 96 Fellows and 169 members, a gain of 21 Fellows and a loss of 30 members for the year. Several members have been dropped on account of non-payment of dues and 13 new members have been added. Two Fellows, Dr. E. O. Hovey and Dr. T. L. Watson, have died, and a brief account of their careers will be published in the Journal. In addition to the 265 Fellows and members, there are also 103 subscribers, chiefly

libraries and colleges, so that there are 368 paid copies of the Journal mailed monthly. It is requested that every effort be used to increase the number of members and subscribers, in order that additional funds may be secured to enlarge the size of the Journal. Fifty-seven Fellows and members, as well as additional guests and visitors, attended the meeting, which, like the previous one, was the largest in the history of the Society.

REPORT OF THE TREASURER

The Treasurer, A. H. Phillips, read his report, which showed a favorable financial balance. In view of this favorable statement, the Council has ordered an 8 per cent increase in the size of the Journal for the coming year.

On motion, the report of the Treasurer was accepted, ordered filed, and an Auditing Committee was appointed by the President. This committee, consisting of Dr. W. T. Schaller and Prof. E. H. Kraus, later reported to the Secretary that they found the books of the Treasurer correct.

REPORT OF THE EDITOR

The Editor, W. F. Hunt, read his report, which, on motion, was accepted and ordered filed. This report showed a favorable growth of the Journal as in the previous year and indicated that the size might be increased again without a financial loss on the part of the Society.

REPORT OF THE COMMITTEE ON NOMENCLATURE AND CLASSIFICATION OF MINERALS

The work of the committee was delayed by the death of the chairman, Prof. Thomas L. Watson, and the Council voted that Prof. Esper S. Larsen be added to the committee, and that Henry S. Washington assume the duties of chairman. The committee now consists of H. S. Washington, W. F. Foshag, A. F. Rogers, T. L. Walker, E. T. Wherry, and E. S. Larsen. Doctor Washington reported that the work interrupted by Professor Watson's death would be carried out, and also that a conference with British mineralogists had been held, and that an international committee would probably be formed. If such a movement leads to anything, the Mineralogical Society of America may congratulate itself that it is due to its own initiative in appointing a Committee on Nomenclature and Classification at the very beginning of the Society.

PRESENTATION OF PAPERS

There being no further business, the presentation of scientific papers was then taken up as follows, according to the program:

BENTONITE AND MONTMORILLONITE

BY CLARENCE S. ROSS AND EARL V. SHANNON

BENTONITE AS A ONE-DIMENSIONAL COLLOID

BY EDGAR T. WHERRY

Read by Frank R. Van Horn.

TABULATION OF THE ALUMINUM SILICATE MINERALS

BY EDGAR T. WHERRY

Abstract read by Frank R. Van Horn.

STUDIES IN THE MICA GROUP

BY A. N. WINCHELL

NEW THEORY OF THE COMPOSITION OF THE ZEOLITES

BY A. N. WINCHELL

CAMSELLITE FROM CALIFORNIA

BY ARTHUR S. EAKLE

FOSHAGITE, A NEW CALCIUM SILICATE FROM CRESTMORE, CALIFORNIA

BY ARTHUR S. EAKLE

NOTE ON THE CRYSTALLIZATION OF THAUMASITE

BY ARTHUR S. EAKLE

JOINT SESSION WITH THE GEOLOGICAL SOCIETY OF AMERICA

At 12.15 p. m. the Society adjourned to the Auditorium of the Baker Chemical Laboratory to attend a joint meeting with the Geological Society of America, at which Dr. Henry S. Washington delivered his presidential address: "The modern study of minerals," which will be printed in full in the March number of the American Mineralogist.

SESSION OF WEDNESDAY AFTERNOON, DECEMBER 31

PRESENTATION OF PAPERS

At 2.15 p. m. President Washington called the meeting to order, and the reading of papers was proceeded with as follows:

TEMPERATURE-PRESSURE CONDITIONS DURING THE FORMATION OF SMOKY QUARTZ AND AMETHYST

BY EDWARD F. HOLDEN

EVANESCENT PINK SODALITE, OR HACKMANNITE, FROM NEAR BANCROFT, ONTARIO

BY T. L. WALKER AND A. L. PARSONS

ELECTRICAL CONDUCTIVITY OF ORE MINERALS

BY PAUL F. KERR AND CHARLES K. CABEEN

COMPUTING AND DIRECT READING JOLLY BALANCE

BY EDWARD H. KRAUS

CALCIFIED LOG FROM THE PITTSBURG COAL NEAR MORGANTOWN, WEST VIRGINIA

BY CHARLES R. FETTKE

PRELIMINARY REPORT ON THE CRYSTAL STRUCTURE OF SOME METALLIC SULPHIDES

BY LEWIS S. RAMSDELL

CHARACTERISTICS OF PRIMARY CALCITE IN IGNEOUS ROCKS

BY T. L. WALKER AND A. L. PARSONS.

SPACE GROUP OF DIOPSIDE

BY R. W. G. WYCKOFF AND H. E. MERWIN

X-RAY DIFFRACTION MEASUREMENTS ON THE DIOPSIDE-LIKE PYROXENES AND THEIR BEARING ON THE NATURE OF AUGITE

BY R. W. G. WYCKOFF, H. E. MERWIN, AND H. S. WASHINGTON

THE CRYSTALLOGRAPHY OF SUCROSE

BY A. F. ROGERS

AN INTERESTING AND USEFUL PROPERTY OF ZONES

BY A. F. ROGERS

NEW TYPE OF SAND CALCITE CRYSTALS FROM MONTEREY COUNTY, CALIFORNIA

BY A. F. ROGERS AND R. D. REED

FULGURITE FROM SOUTH AMBOY, NEW JERSEY

BY W. M. MYERS AND ALBERT B. PECK

Abstract read by W. F. Hunt.

The last paper was finished at 5.25 p. m., after which Prof. E. H. Kraus moved that the thanks of the Society be extended to the local committee, and to the President and the Trustees of Cornell University for their kindness and hospitality. This was adopted by a rising vote. The Society then adjourned.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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METASOMATISM

PRESIDENTIAL ADDRESS BY WALDEMAR LINDGREN[1]

(*Read before the Society December 28, 1924*)

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WHAT IS METASOMATISM?

I shall begin somewhat bluntly by asking the question, "What is metasomatism?"

Perhaps I am right in saying that there is a general impression abroad that metasomatism is a sort of replacement of one mineral by another, with addition of material and mainly of importance in ore deposits. I would like you to look at it from a far broader viewpoint—as a universal process based on the fact that the minerals of all rocks are soluble in the fluids of nature, particularly water, but also in the mixed emanations from magmas, and on the fact that these fluids change the minerals to others, of different composition, stable under the particular conditions of pressure and temperature prevailing. Remove metasomatism and there would be very little left of metamorphism.

I would define metasomatism as *an essentially simultaneous, molec-*

[1] Manuscript received by the Secretary of the Society January 14, 1925.

ular process of solution and deposition by which, in the presence of a fluid phase, one mineral is changed to another of differing chemical composition.

Replacement is regarded as synonymous with metasomatism, but the latter term is preferred, as it may be adopted in all languages. *Alteration, dissemination,* and *decomposition* are synonymous with certain phases of metasomatism.

Metasomatism is, no doubt, governed by the laws of thermodynamics, but their application is greatly complicated by surface phenomena. The law of mass action helps to explain many reactions of metasomatism in open space, but does not always afford a safe basis for the interpretation of changes going on in capillary spaces.

Metasomatism is at times governed by the phase rule, but in replacements in solid rocks and under stress the phase rule is not directly applicable; neither is it applicable in gel-replacements.

Metasomatism is at times governed by simple equations and definite stoichiometric relations; but replacements by crystalloids in solid rocks rarely follow these equations and in gel-replacements no formulas can be written. Nevertheless, the process is molecular in the sense that solution changes the equilibrium in the solvent, so that precipitation must occur; but the process does not always proceed "molecule for molecule."

In open space, in liquids and similar yielding media (gels), metasomatism is generally governed by the law of mass action and by the phase rule. I do not feel sure that it is so governed in rigid media.

Metasomatism draws no distinctions between partial and complete replacement. Pyrite replacing feldspar, galena replacing calcite, epidote replacing soda-lime feldspar, silica gel replacing limestone—all are phases of metasomatism.

Metasomatism may or may not proceed with changes of volume. In open space, in liquids, in soft rocks, and in gel-replacement there is usually a change of volume. In solid rocks the volume of the replacing mineral or minerals is substantially equal to that of the mineral or minerals replaced.

Specifically excepted from metasomatism are processes of paramorphism, in which by molecular rearrangement one mineral changes to another space lattice, as, for instance, when isometric chalcocite is transformed to the rhombic modification; also excluded are unmixing processes, as when a solid solution at a certain temperature ejects part of its dissolved material in crystalline form—for example, when in cooling galena silver sulphide is separated.

I have at the outset outlined my conception of metasomatism, for the current views on this matter are rather markedly divergent.

As stated above, some investigators divide metasomatism in these cases where no chemical reaction can be written, and in others where the process progresses according to certain supposed chemical equations. There appears to be no need of such a distinction. A precipitate may result from a double decomposition, but it may as well be caused by physico-chemical changes in the solution rendering insoluble a substance foreign to the attacked mineral.

Prof. V. M. Goldschmidt,[2] of Kristiania, in a paper of great merit, has recently proposed a definition of metasomatism. Grubenmann and Niggli,[3] in their splendid volume on metamorphism, also follow a similar trend of opinion. These authors wish to narrow metasomatism to rocks, speaking of metasomatic rocks when *essential* changes of composition have taken place. Goldschmidt defines the term as follows: "Metasomatism is a process of alteration which involves enrichment of the rock by new substances brought in from the outside. Such enrichment takes place by definite chemical reactions between the original minerals and the enriching substances." Water and carbon dioxide are excepted from "new substances."

I wish to enter a strong protest against such an unwarranted emasculation of a useful and fundamental conception. In the first place, metasomatism should be a term applied to individual minerals; if they are changed in composition by alteration, these new minerals are metasomatic. If the whole rock also changes in composition, then the rock also is metasomatic; and no exceptions are to be allowed for privileged substances. As to the last part of Goldschmidt's definition, referring to "definite chemical reactions," it is assuredly wrong. If calcite or limestone is replaced by quartz, or cryptocrystalline silica, then surely the new silica is a metasomatic mineral and the limestone is a metasomatic rock; but the process involves no definite chemical reactions, simply a precipitation of quartz or silica gel for which no equation can be written.

The absence of a definite word for the process here described is painfully felt in perusing the volume on metamorphism by Grubenmann and Niggli. They use such expressions as "Neubildung," "Umbildung," "Umsetzung," "Reaction." "Verdrängung," which is really the equivalent of replacement, is very seldom used.

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[2] V. M. Goldschmidt: Metasomatic process in silicate rocks. Econ. Geology, vol. 17, 1922, pp. 105–123.

[3] U. Grubenmann and P. Niggli: Die Gesteinsmetamorphose. 1. Allgemeiner Theil. Berlin, 1924.

Crystalloid Metasomatism in solid Rocks

For the present purposes I shall not deal in detail with these phases of metasomatism which take place in yielding media. The ordinary rules of chemistry generally hold here. The following remarks apply to metasomatism in rigid rocks, in part also to metasomatism in rocks subject to strong plastic deformation.

In the first place, I would like to point out that it is immaterial to the process of metasomatism, as outlined here, whether the metasome (the "guest") consists of elements foreign to the host—that is, galena in calcite or pyrite in orthoclase—or has one or more components in common—that is, fluorite in calcite, or chlorite in augite, or wollastonite in calcite. The process is essentially the same. Who shall say, for instance, when chalcopyrite replaces ankerite or pyrite replaces hornblende, just how much, if any, of the iron is derived from the host mineral and how much is introduced? Or how much, if any, lime is derived from the host when ankerite replaces oligoclase? Is it an entirely different process when ankerite replaces orthoclase?

Replacement may (1) preserve the form of the host by an individual metasome—for example, chlorite after biotite; (2) preserve the form of the host by aggregate structure—for example, chalcocite after pyrite; (3) proceed without preservation of form, as irregular aggregates—for example, calcite in feldspar—or by developing well-defined "metacrysts" in the host—for example, pyrite in hornblende; (4) replace one aggregate of several minerals—for example, cyanite in schist or pyrite in slate.

In the second place, I wish to reaffirm the thesis of which I have frequently spoken in the past, that in solid rocks the volume of the metasome, or metacryst, is substantially the same as that dissolved from the host. I say substantially, first, because of the pore space of subcapillary openings created when an aggregate like sericite replaces feldspar; and, second, because when the attacking solutions are sufficiently abundant active solution may run ahead of deposition and a drusy structure may result. In metamorphism[4] there are no drusy structures, because the changes proceed slowly. The rule of equality of volume has been found true by the work of many geologists who have paid any attention to the case. The textbooks, including the latest, generally preserve a discreet silence. Grubenmann and Niggli, in their latest edition of "The Metamorphism," 1924, admit that in some cases of "metasomatic ore deposits" constancy of volume may be true.

[4] The term of "metamorphism" as here used excludes weathering.

I would like to have the doubters carefully examine some crystals of epidote developing in soda lime feldspar or rhombs of calcite, dolomite, or ankerite replacing feldspars or tourmaline prisms developing in various rocks and see if there is any escape from this proposition.

To explain metasomatism (as here defined), Goldschmidt and Grubenmann and Niggli, as well as other authors of textbooks, depend entirely on the law of mass action and on the phase rule.

This is really a chemical problem, and I am not a chemist. Probably something will be said about rushing in where others fear to tread, to put it mildly. If in error, I shall be glad to be corrected.

It is certain, of course, that the phase rule does not apply to colloidal systems. Niggli admits that it does not hold where stress and unequal pressures in the system are present. It seems to be extremely doubtful whether it can be applied where capillary or subcapillary chemistry are concerned. Gibbs himself excludes the effects of capillarity;[5] and if this is so, its use in metamorphism seems highly questionable. In a subcapillary system the surface tension and the adsorbed layer play important and not fully recognized parts. The phases become difficult to recognize and the pressures are probably not the same in all parts of the system. As well known, the phase rule can be applied only to systems of equilibrium.

At the meeting of the Geological Society of America in 1923 (volume 35, number 1), D. F. Hewett presented a paper on dolomitization in which it was pointed out that at the locality described there was no evidence of contraction in volume. In discussing this paper R. B. Sosman remarked "that the flow of liquids in capillary spaces is evidently accompanied by phenomena not yet clearly understood. It is very probable that some of the phenomena of replacement in nature are of this class and are not reactions which can be represented by the familiar balanced equations of chemistry." I have quoted this as the only example known to me where a chemist has shown an appreciation of the problems related to metasomatism. The fact seems to be that physical chemists are so used to consider systems in equilibrium and reactions in open space or in liquids that they give little attention to other conditions.

As for the law of mass action, it is a useful rule, but subject to many exceptions and irregularities. It seems doubtful to me whether it can be applied to the essentially capillary process of metasomatism in rigid rocks. The question simmers down to the query: Is the law of equal volume a fact in metasomatism of solid rocks or is it not? If

[5] W. Ostwald: "Handbook of colloid chemistry," footnote, p. 105.

solid zinc carbonate replaces limestone with complete preservation of structure, then the equation.

$$ZnSO_4+CaCO_3=ZnCO_3+CaSO_4$$

is obviously wrong, for a volume of calcite is replaced by an equal volume of smithsonite ($ZnCO_3$), which requires more Zn and more CO_3 than indicated by the double decomposition. If the equation is true, then contraction must take place. What has actually happened should be expressible by some kind of an equation, but I confess inability to formulate it. Perhaps gel replacement might solve the problem.

May I be permitted to suggest that many eminent geologists who have studied the crystalline schists do not fully realize the nature of metasomatism? It sometimes seems to me that they emphasize the phenomena caused by stress at the expense of the main underlying process, which is metasomatism. They speak, for instance, of the "quartz-tails" and of the peripheral rings of quartz, calcite, or chlorite, which so frequently surround metacrysts (porphyroblasts) in schists, and of the quartz along twinning planes and gliding planes as if they were fillings of open cavities. Grubenmann and Niggli speak of them as "Fefüllte Zerrungshohlräume," while it appears to me that they are nothing but replacements by quartz and other minerals. Entirely similar peripheral rings may be seen in the metasomatically altered rocks which have been subjected to hydrothermal action. The study of the crystalline schists should be preceded by that of ordinary "static," or hydrochemical metamorphism.

Is it not likely that most of the phenomena observed in schists are simple replacements modified in development by the influence of stress, so that solution without replacement predominates at points of maximum stress and deposition with replacement at points of minimum stress? Surely, it is common enough in schists to find inclusions in the metacryst of matrix and abutment of the mica foils of the matrix against the metacryst. This is in places modified by the stress which also tends to produce the rotations which have been so clearly demonstrated by F. Becke and others.

When we find aluminum concentrated in metacrysts of, say, cyanite embedded in a uniform schist matrix, does not this prove a considerable transportation of this element? It is not to be denied that metasomatism may result from the vapor phase between two adjacent grains, or by hydroxyl liberated, or by simple rock moisture; but movement and transportation on capillary openings appear to me as the governing factors. Even in hornfels such movement is in operation, for we find tourmaline and scapolite widely distributed in contact aureoles.

I will go so far as to say that all forms of metamorphism are accompanied by change in composition, though the changes sometimes may be small.

Gel-metasomatism, or replacement of Crystalloids by Gels

When the product deposited during metasomatism is a gel instead of a crystalloid, we may call this process gel-metasomatism. Little attention has been given to this in the past, but it looks now as if its importance had been greatly underestimated. Many chemists hold that any precipitate must pass through a gel-stage, even if it is only momentary. To any one familiar with the lightning-like development of crystals under the microscope, this seems an exaggeration; yet it may well be true. It is known, for instance, that many substances, like sodium chloride or barium sulphate, which ordinarily seem far away from the gel-state, can be obtained as jellies.

Gels are obtained in many ways, among which I shall only mention double decomposition, mutual precipitation of sols, or precipitation of sols by electrolytes. Even when obtained by double decomposition, they are rarely pure, but contain adsorbed material and, in the case of sulphides, more or less colloidal sulphur. When obtained by the two latter methods mentioned, no simple stoichiometrical relationships exist between the coagulated product and the precipitant, and adsorption is always an important factor.

In rocks the reactions are carried on as in crystalloid metasomatism on subcapillary fissures. Surface tension, surface energy, and the adsorbed layer play important parts. The phase rule as well as the mass law does not apply. Diffusion is of great importance, supplementing circulation, for electrolytes readily penetrate the gels. As a rule, no stoichiometrical formulas can be written. The precipitate takes the form of a gel, and it is probably of a high degree of concentration. The spaces provided by solution are practically at the same moment filled, and the law of equal volume undoubtedly holds. If larger pores and cavities are present in the rock, these will ordinarily be filled before metasomatism begins.

There is this difference, however; in gel replacement, the rock tends to become a mass of soft material, subject to contraction, fracture and crushing, so that ultimately sudden volume adjustments may take place.

The gel has a great tendency to colloform structure, replacing the host minerals in concentric rounded masses. This structure is not always developed, however.

Crystallization usually occurs sooner or later, and the gel becomes a metacolloid or a mixture of metacolloids, ordinarily a definite mineral or minerals and very frequently arranged in radial-fibrous forms. Sometimes crystallization may follow very closely on the heels of the separation of the gel. This is commonly accompanied by reduction of volume and expulsion of water. We, therefore, often find the metacolloids fractured or showing concentric contraction cracks, empty or filled with minerals of different kinds—calcite, for instance, or a new gel deposit.

Of course, the question may be raised whether gel-replacement is covered by the definition given in the beginning of this address. It may be said that a gel is not a mineral. A mineral is usually defined as an inorganic body of definite chemical composition found in the crust of the earth. A gel may not have a definite chemical composition and it may crystallize to two or more minerals. There are, however, many hardened colloids of varying composition—as, for example, the copper pitch ores and varieties of chrysocolla—and it is a question whether the "definite chemical composition" can be upheld.

It may also be pertinently asked, How do you know that these so-called "gel-replacements," now crystalline, have actually passed through the gel stage? What are the deciding criteria? In answer to this it may be said that at times the proof can be given along several lines and be wholly convincing, as I think I have done in case of the replacement of limestone by silica gel in Professional Paper 107, on the Tintic district. At times the proof can not be complete, especially when the colloform structure is absent. The safest criterion is undoubtedly that afforded by these concentric and concretionary structures.

The matter of spheroidal forms in minerals has been discussed by many authors since the days of Roth. Lately, A. F. Rogers and H. C. Boydell have contributed to the study of such criteria. Spheroidal forms result from weathering and abrasion, and they appear also in magmas, as shown by the occurrence of spherulitic and orbicular structures. Spheroidal forms may also result from diffusion of electrolytes in gels and in porous substances, as has been most efficiently pointed out by Liesegang.

In general, spheroidal development in a homogeneous substance strongly suggests the effects of surface tension in a viscous medium. Boydell says that "concretions of colloidal origin can result from inorganic as well as from organic processes. The mineral forms described as botryoidal, mammillary, reniform, spheroidal, stalactitic, are all manifestations of surface tension effects in viscous material, and therefore are indicative generally, though not by any means exclusively, of col-

loidal origin." It seems to me that when a homogeneous material develops such structures they are the best criterion of a previous gel state, especially when they are emphasized by the successive deposition of thin concentric layers of slightly different appearance or show distinct concentric contraction cracks. Such structures may develop by replacement as well as in open space.

In gel-replacement the concentric contraction cracks, when present, are directed with the convex side outwards in the general direction of the reaction. They do not follow the outlines of the space now occupied by the gel mineral, as would most likely be the case if the latter had filled a preexisting cavity.

Occurrences of Gel-replacement

General statement

It is perfectly natural that gel-replacement should be most prominent in the zone of oxidation and in semi-consolidated sediments. To some extent it may take place during sedimentation. It is also very common in the zone just below that of active oxidation. Its importance in ore deposits of the epithermal and mesothermal kind is just beginning to be appreciated. It is not common in ore deposits of hypothermal or direct magmatic origin. In metamorphism it is also generally absent, but it abounds in ordinary rock alteration under near-surface conditions.

In the zone of oxidation

In the loose, or at least more or less softened, masses of decomposed rock many colloid precipitates are undoubtedly forming in open spaces and in pores, for precipitation favors open spaces; in this zone, particularly near its base, larger colloform masses are frequent—of limonite, of psilomelane, of barite, of wavellite, or smithsonite, or many other substances. I believe that in the majority of cases these represent replacements of the regolith by gels, which soon acquire crystalline structure. If occurring in the mass of rock, they either fill open spaces or they are replacements. Open spaces of this form and size are unlikely. The gel certainly did not push the rock apart. Therefore the probability rests with the replacements theory. The earlier work of T. L. Watson and E. C. Harder seemed to indicate this origin for psilomelane quite clearly; and recently D. F. Hewett has taken the definite stand that in most cases psilomelane develops by such a process, although he does not emphasize the original gel character of the mineral. It is evident that this manganese mineral replaces clayey soil as well as various inclusions of rock

in the soil; and the same doubtless applies to limonite. The hydroxide gels are probably precipitates from carbonate or sulphate solutions.

IN PARTLY CONSOLIDATED SEDIMENTS (DIAGENESIS, ANDREE)

Solutions yielding colloidal precipitates are constantly at work in soft sediments. Glauconite and other iron silicates, phosphates, siderite, and many others are formed by adsorption, mutual precipitation of colloids, or electrolytic coagulation. In the oolites no doubt gel replacement is going on to some degree (halmyrolysis, Hummel). I believe the majority of concretions like those of marcasite, siderite, and barite are gel-replacements in the first place which later have acquired crystallinity. That means that the soft material around the incipient concretion has been dissolved and that simultaneously a gel has been precipitated, at first assuming colloform outlines. Such concretions have been explained by Liesegang as caused by diffusion, and undoubtedly diffusion plays an important part; but they can not be caused by "cementation" (Verkittung, Liesegang), for they are essentially pure and must have *replaced* material once occupying their space.

IN METAMORPHISM

The tendency of many members of the chlorite group to assume colloform shapes is emphasized in many textbooks of mineralogy. Among these the iron-bearing chlorites predominate, such as thuringite, cronstedtite, diabantite, and delessite. No doubt the delessite lining amygdaloid cavities is a colloidal precipitate. Many petrographers have called attention to the frequent development of chlorite in "pseudoamygdules." A chloritized greenstone may be filled with these rounded chlorite aggregates, which strongly suggest that from certain centers the rock substance has been dissolved with simultaneous precipitation—that is, replacement—of iron-magnesium-silicate gel. This subsequently acquired the cryptocrystalline structure of a metacolloid.

It has often occurred to me that serpentinization may also, in part, at least, be a gel-replacement, though of this I am not as yet able to furnish definite proof.

IN ORE DEPOSITS

General statement.—It is now evident that gel-replacement plays a considerable part in the development of some ore deposits, principally of the epithermal or mesothermal kind. We may differentiate between replacements of supergene and of hypogene origin.

Replacements of probable supergene origin.—In the zone of oxidation gel-replacements are constantly going on. I shall only mention a few instances. Minerals like chrysocolla, copper-pitch ores, some malachites, some jarosites, and some zinc carbonates are clearly metacolloids and have passed through a distinct gel-stage. In a large number of cases it will be found that these are not deposited in open space, but owe their origin to gel-replacement.

Just below the zone of oxidation among the "secondary sulphides" we find many more examples. It is maintained by Tolman that many chalcocites are of gel-origin. This has been denied by Schneiderhöhn, but I believe it is true, particularly of these "sooty" forms which owe their origin to precipitation of cupric sulphate by hydrogen sulphide generated by the action of sulphuric acid on older sulphides. I think it is very likely that some at least of the replacements of pyrite, chalcopyrite, etcetera, by chalcocite are real gel-replacements.

The second instance is the development of marcasite just below the zone of oxidation. The first time I observed this was in an ore from the sulphide deposit of the Iron Queen Mine, near Mayer, Arizona. Here marcasite with colloform structure freely replaces the gangue minerals, mainly quartz, as well as sphalerite and perhaps pyrite (United States Geological Survey publication, in press). About the same time W. H. Newhouse, of the Massachusetts Institute of Technology, found entirely similar occurrences at Kokomo, Colorado, and in the ores of the Angangeo district, Michoacan, Mexico. Here, too, quartz and pyrite were replaced by marcasite showing colloform structure and, in places, contraction cracks (Economic Geology, paper in press). The process is later than the main mineralization, and it is believed that it took place just below the water level. An entirely similar case from Ducktown has been already described by G. Gilbert in the Transactions of the Institute of Mining and Metallurgical Engineers for 1924. He found marcasite with colloform structure replacing pyrrhotite or sphalerite, but not pyrite or chalcopyrite. A colloidal origin is not considered, but excellent photographs are presented. The process is explained by solution of pyrrhotite by sulphuric acid and the action of the resulting hydrogen sulphide on the ferrous-ferric sulphates. Under such conditions, I believe, a gelatinous precipitate of FeS and S should result and the colloidal mixture would crystallize to FeS_2. Similar occurrences of marcasite were observed by Gilbert from the Great Gossan Lead, Virginia, and Rossland, British Columbia. Two articles (Watanabe and Landwehr; G. A. Thiel) in a late number of Economic Geology refer to a phenomenon

of the same kind, though they do not expressly interpret it as of colloidal origin.

Several years ago, in a paper on the Tintic district, I mentioned that marcasite or pyrite was found in concentric rings as a replacement of gangue in an ore from the Gemini Mine, believed to have been subjected to alteration below the water level. In the same report is described colloform sphalerite replacing a dolomitic breccia.

Replacements of hypogene origin.—Many geologists have explained the formation of certain kinds of chert in limestone and of silicified fossils with complete preservation of sculpture by means of a gel-replacement. Experimental demonstration of such replacement was furnished by A. H. Church many years ago.

The silicification of limestone and dolomite near ore deposits is often a normal crystalloid replacement. J. D. Irving was the first, I believe, to describe a different kind of silicification in the ore deposits of the Black Hills, South Dakota. More recently I have called attention to the entirely similar replacement phenomena in the Tintic district, Utah, and showed that we here undoubtedly had to deal with a gel-replacement at temperatures of, say, 200 degrees to 300 degrees centigrade. In contrast to the crystalloid replacement, which begins at numerous points in the rock by the development of individual quartz metacrysts, the gel-replacement proceeds like a wave, uniformly substituting a gel, which soon after crystallizes to a micro- or crypto-crystalline aggregate of silica, often with perfect preservation of structure.

A chemical explanation has been furnished later by Cox, Dean, and Gottschalk, who found that when a colloidal solution of silica containing CO_2 was allowed to act on calcium carbonate the silica is rapidly precipitated by the positively charged calcium ions of the dissociated carbonate. Without CO_2 no reaction takes place. It is evident that no equation can be written for this reaction, and that it is governed by no ordinary stoichiometrical rules.

Colloidal silica subsequently crystallized is often precipitated in the fissures of the epithermal deposits, and gold, for instance, is surely carried in the colloidal state in such solutions and so deposited. I hasten to add that I do not believe that the gel has been injected, but that it has gradually been deposited from aqueous solutions.

Seldom do we find evidence that the metallic minerals in ore deposits were precipitated as gels, either in open space or by replacement. There are some exceptions, however. Native arsenic or arsenic-antimony (allemontite) is characteristically deposited as colloform masses, and this

occurs in many deposits. In part they may be formed in open space. Most of the cases I have seen indicate gel-replacement of calcite or quartz. The mineral occurs in the solid vein material as colloform, kidney-shaped masses crystallized soon after the replacement. Formerly I have held the mineral to be of supergene origin, not realizing the mechanics of gel-replacement. It is evident now that this view was erroneous. As far as I know, Prof. J. L. Gillson was the first to demonstrate the hypogene origin of native arsenic, this in a United States Geological Survey publication now in press. Such colloform arsenic occurred at Freiberg, Coromandel (New Zealand), Camp Washington (Arizona), Pend'Oreille district (Idaho), the Engineer Mine (Yukon), and many other places. At the Engineer Mine it is accompanied by native gold and roscoelite, and it is an interesting fact that at this locality the roscoelite (a vanadium mica) also shows distinct evidence of gel origin. It is well known that minerals containing vanadium and arsenic have a strong leaning towards colloidal behavior.

My attention has lately been attracted to the very strong tendency to colloform structure among the arsenides and sulpharsenides of cobalt and nickel. Perhaps this is most marked in niccolite. Over here we are disposed to regard the silver-bearing veins of Cobalt, Ontario, as something rather unique, with their gangue of calcite and their complex mineralization of niccolite, smaltite, chloanthite, arsenopyrite, löllingite, cobaltite, breithauptite, and many other similar minerals. However, if we glance through some such works as Hintze's "Mineralogie" or La Croix' "Mineralogie de la France," we soon find that this peculiar association of minerals and types of structure are exactly the same as those of a dozen long-known European deposits, though these latter may lack the phenomenal richness in silver peculiar to the veins of the Cobalt district. Concentric and concretionary structures are extremely common.

A careful study of the Cobalt deposits have led me to believe[6] that we have here one of the most instructive examples of gel-replacement at higher temperatures. As is well known, the narrow veins stand in genetic relationship to the thick, intrusive sheet of diabase. The veins have been described by many geologists, and at least six of them, William Campbell and C. W. Knight, W. G. Miller, E. S. Bastin, H. V. Ellsworth, and W. L. Whitehead, emphasize the concretionary and con-

[6] This conclusion was reached simultaneously by Dr. H. C. Boydell and the writer and is referred to in Dr. Boydell's notable dissertation on "The rôle of colloidal solutions in the formation of mineral deposits," which has just been published in the bulletins of the Institution of Mining and Metallurgy (London). This writer, however, holds that the arsenides were deposited in a "carbonate gel."

centric structure of the ore, though they do not draw the inevitable inference as to the mode of origin. The veins are generally considered as mesothermal—that is, formed at intermediate temperatures, probably not exceeding 250 degrees centigrade.

At Cobalt the deposition may be divided in three stages:

1. The filling of the fissures by crystalline calcite and dolomite.

2. The replacement of the carbonates by gels of arsenides and sulpharsenides.

3. The introduction, mainly by replacement, of crystalloid native silver.

On polished faces the colloform arrangement of the arsenical minerals becomes particularly clear. Rounded, often concentric, aggregates appear in the carbonate and sometimes even extend into the wall rock. Niccolite cores are common and are usually surrounded by rounded, concretionary deposits of smaltite and other minerals. Under the microscope the solid aggregates are resolved into extremely intricate intergrowths, in which it is next to impossible to recognize any definite succession, but they are just what would be expected from the sudden crystallization of a complex gel. With considerable confidence I advance the view that the arsenical minerals are a gel-replacement of an older, crystalline carbonate filling.

It is obviously difficult to explain the chemistry of such a complex process, but here is a crude outline of what may have taken place.

The second stage consisted in the introduction of mobile solutions emanating from the cooling diabase. They may have been more or less mixed with water of magmatic or meteoric origin. They consisted of the chlorides of cobalt, nickel, and iron, and were mixed with arsenic sulphide (colloidal?) and hydrogen sulphide or alkaline sulphides. The immediate precipitation was inhibited for the time by the acid conditions resulting from hydrolysis of the ferric chloride. These solutions attacked the country rock—diabase or argillite—slowly or not at all, while an intense reaction was set up as soon as they encountered the carbonate filling. This resulted in the solutions becoming neutral and the sulphides, together with sulphur and arsenic, were precipitated as a complex gel, which took the place of the dissolved calcite after the fashion of gel-replacement. Needless to say, the liberated CO_2 must have played an important part in this system.

The complex gel was almost immediately transformed into crystalloids, resulting in the mixture of minerals which we now find. The crystallization was accompanied by contraction and fissuring, but the spaces were immediately filled by calcite or newly precipitated gel. The con-

centric gel-banding is often clearly visible. Because the crystallization followed so closely on the heels of the gel-precipitation, it is not surprising that we find places where crystals were formed directly in the country rock or in the vein filling, but they do not appear to be the principal mode of ore formation.

I believe the silver also came from the diabase magma, but in this reaction, as far as known, no colloidal processes were involved.

In the deposits formed at higher temperatures, definite evidence of gel-deposition and gel-replacement are lacking as a rule. We know of one instance, however. In 1916 Adolph Knopf described tin bearing veins in rhyolite from Nevada. The minerals consist of concentric wood tin, with opal, chalcedonic silica and specularite. Indeed, Mr. Knopf says that "locally the rhyolite has been replaced by wood tin, hematite and the various silica minerals." The author strongly maintains the colloidal nature of this occurrence.

Conclusion

I fear having tried your patience by an address grown longer than anticipated. I have had two objects in view: First, to restore metasomatism in general to its proper place in the study of the alteration of rocks; and, second, to call attention to the neglected field of colloidal replacement. Substantially the process is of the same type, whether a chemical equation can be written for it or not, and whether the product is a crystalloid or a gel.

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ON CORRELATION

PRESIDENTIAL ADDRESS BY EDWARD W. BERRY[1]

(Delivered before the Paleontological Society December 30, 1924)

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INTRODUCTION

The most important phase of both geologic chronology and stratigraphy is the precision of correlation. Not only is this true, but precise correlation is the only scientific basis of the biological problems concerning the origin, dispersal, and distribution of faunas and floras and particular stocks. Moreover, since distribution and the paths of dispersal constitute the fundamental data of all paleogeographic studies, it is obvious that what might be called historical geology in the largest sense ultimately rests on the success with which correlations are made.

Many students in the past have discussed the criteria for correlation from varying points of view, and there have been numerous symposia before the Geological and Paleontological Societies in which particular problems of correlation have been discussed and in which the methods employed were exemplified.

I propose to refer but incidentally to some of these earlier discussions, nor is it necessary to attempt a careful historical résumé of the gradual

[1] Manuscript received by the Secretary of the Society January 16, 1925.

building up of the geologic column as we know it at the present time by the combined forces of stratigraphy and paleontology.

Historically, what might be considered as correlation was in its beginnings based upon lithologic (mineralogic) criteria, as might be expected. If we examine the first prototype of a geologic map, that of Guettard in 1746 (Jean Étienne Guettard 1715-1786), we find mapped what that author called mineral bands, and there appears to have been no idea of chronologic relations.

The first exponents of geological succession—Lehmann, 1756 (Johann Gottlob Lehmann, -1767), and Fuchsel, 1762 (George Christian Fuchsel, 1722-1773)—may be said to have employed the two criteria, lithology and succession, for correlating the younger rocks of small areas in Germany.

If we examine the works of the real fathers of stratigraphy, namely, William Smith[2] in England (1801) and Cuvier[3] and Brongniart[4] (1808) in the Paris basin, we find three criteria taken into account, namely, lithologic similarity, succession, and fossil content, and I think all geologists will admit that the recognition of this third criterion, or stratigraphic paleontology, furnished the real starting point to stratigraphy and geological chronology.

The reaction against a purely paleontologic basis for correlation has been gathering force for several decades and was doubtless merited. I should like to point out, however, that the imperfection of the paleontologic method, so often exemplified, was not really due to the intrinsic worthlessness of the fossils, but to lack of understanding on the part of the paleontologist, for with Ulrich I firmly believe "that fossils in experienced hands afford by far the most competent and reliable evidence now available in stratigraphic correlation" (Revision, page 292).

To me the study of paleontology includes the environment, both organic and inorganic, and it is quite futile to consider faunas and floras apart from the theater of life in which they played their part. Too many paleontologists still consider fossils in the pre-Zittelian sense, as merely fossils, things dug, rather than as live dynamic organisms. This consideration of the environment applies with particular force in the study of impressions of plants, which play such an important part in the work of the paleobotanist.

Consider, for example, the foliage of the flowering plants, which class of remains predominates in the fossil record of Upper Cretaceous and

[2] William Smith, 1769–1839.
[3] Georges C. L. D. Cuvier, 1769–1832.
[4] Alexandre Brongniart, 1770–1847.

Tertiary times. The species are to be numbered in hundreds of thousands, and because of this many of the determinations are empirical, and the most competent paleobotanist is the one who knows the most plants. Shall we, then, maintain with Seward, that the fern genus Kaulfussia can not be distinguished from Aralia, Bombax, or Æsculus; or that Polygonum, Equisetum, Casuarina, Ephedra, Frenela, and Restio are liable to confusion; or that the Proteaceæ, Comptonia of the Myricaceæ, and Lyonthamnus of the Rosaceæ are indistinguishable; or that we are called upon to decide between the umbelliferous herbaceous genus Eryngium and the trpical monocotyledonous genus Pandanus?

Seldom, if ever, are these alternatives actually encountered. In the first place, whether or not we subscribe to the view that herbaceous plants were a late evolutionary product, it is certainly true that their chance of preservation as fossils is much less good than in the case of arborescent forms, and they are almost absent in the geologic record, except as fruits and seeds in the late Tertiary and Pleistocene formations. No competent student of fossil floras need be lacking in some knowledge of the probable place of origin of a particular flora or something of the environment in which it flourished, and this environmental facies will often be the most important clue to generic determination in doubtful cases.

Let me stress, then, the point that the paleontologist must be broadly trained and capable of synthesizing all of the criteria in arriving at a judgment. He must know not only plants and animals, but their habits and habitats, and mutual relations to one another and to their environment.

This may seem trite; but recall how few paleontologists who would not disavow a belief in Cuvier's catastrophic philosophy, and yet how few whose conclusions regarding correlation are not reasoned out on a purely catastrophism—special creation basis.

Our interpretation of the past is, then, very largely conditioned by a sound philosophy. Shall we, then, subscribe to uniformitarianism or catastrophism? Shall we believe with J. C. Willis[5] that time and not adaptation is the key to facies? Shall we, with Matthew, regard primitive forms as most remote from their ancestral home, or shall we subscribe to the doctrine of Chamberlin, that diastrophism is the fundamental basis of correlation? I propose to comment on these and other alternatives.

[5] J. C. Willis: Age and area, 1922.

Diastrophism

To what an extent the underlying philosophy influences the results may be readily demonstrated by contrasting the classifications reached by Ulrich and Schuchert in recent years. The problem of correlation would be immensely simplified if it could be demonstrated that diastrophism was world-wide and periodic, as Chamberlin contends, and this is one of the reasons for its attractiveness to stratigraphers; but in many ways this conception is strikingly like Werner's teaching, and, to my mind, equally untenable.

Even a limited acquaintance with the succession of events in the geological history of a single continent, much less all of the continents, demonstrates the falsity of either the world-wide synchroneity or the periodicity of displacements of the strand-line. In North America and Europe, the two continents that have been studied longest and are the best known, we find a total lack of synchroneity in movements of the strand, not only when the two continents are compared with one another, but even when the Atlantic and Pacific coastal regions of North America are contrasted, or those of Mediterranean and northern Europe.

Certainly it is true in the chapters of geologic history available for study that the altitude of the land, its location with respect to the antecedent sealevel, the nature of the local movements, and other factors—all influence the result, and even in such relatively circumscribed areas as the Paris basin or the Mississippi embayment during Cretaceous and Tertiary times the lithology and the breaks in sedimentation are often not concordant, and two such near regions as the Paris and Rhone basins are in striking contrast. Ulrich has shown that Newberry's conception of cycles of sedimentation are inadequate when applied to the North American Paleozoic, and I can not see any basis for Bailey Willis's so-called law of periodicity.

Many illustrations might be given from the part of the geologic column that I am most familiar with, namely, Mesozoic and Cenozoic, to show discordant diastrophism, even with respect to the so-called major breaks. I will mention but one—the boundary between the Lower and Upper Cretaceous. This is clearly defined in some regions, but unrecognizable by diastrophic criteria in others in the same basin. The same seems to be true in some region of the systemic boundaries between most of the systems.

I can not see that historical geology has reached a point as yet where the stratigraphic succession of rocks can be wedded to our concept of time, so that the need for distinguishing time apart from rocks will

become unnecessary. After all that can be said for them, it remains true that classifications are conveniences for reference and mediums of exchange, and chronologic boundaries are quite as artificial as most political boundaries and far more subjective. Sedimentary units of whatever magnitude have boundaries which are often concrete, but that these will exactly correspond in different regions I much doubt.

Many students seem to be opposed to a dual nomenclature for time and rocks. This, if I mistake not, was the point of view of H. S. Williams, who insisted at the time the rules governing the work on the folios of the United States Geological Survey were under discussion that the system is the unit of the standard stratigraphic scale, whereas the rule adopted reads: "Through correlation all formations are referred to a general time scale, of which the units are the periods. The formations made during a period are collectively designated a system."

Certainly, if the major units of our geologic time table are to be international and not provincial, the latter conception should govern, and the fact that the rock systems differ in their chronologic limits from place to place is conclusive proof that diastrophism is not the ultimate basis of correlation.

It might not be amiss in this connection to again call attention to the somewhat erroneous use of periodicity and rhythm in almost all the more recent discussions of correlation. That there is any geophysical basis for periodicity or rhythm in diastrophism the most competent geophysicists absolutely deny. Both terms mean recurrence after definite regular intervals. It is true that positive and negative movements of the strand follow one another in any single area, and this was the basis for the idea of cycles of sedimentation; but that any two such cycles, however complete, have the same chronologic value is an unproven proposition. Succession is not true periodicity, and I can not see that a cycle of diastrophism is a chronologic unit any more than the life cycle or ontogeny of one organism can be said to equal that of another organism just because both are born, grow, live, and die. All go through such a cycle, but that of a mouse is passed through in a few years, whereas an elephant may live more than a century. One plant may complete its cycle in a single year and a Sequoia may last for thousands of years.

There is only a partial objectivity in the data relied upon to separate critical periods or "revolutions" from those supposed lesser diastrophic changes that H. D. Rogers christened "disturbances" in 1856. That there is a large personal or subjective element in evaluating the observed facts can be realized by comparing the diverse conclusions reached

by different students utilizing the same materials. A major break becomes a minor break or a minor break becomes a major break, according as preconception demands the placing of a boundary at this or that point in the stratigraphic succession.

Similarly, the evaluation of intervals involved in the breaks in the succession by means of what has been called paleophysiography is most uncertain, being dependent to such a large extent upon the elevation and climate.

Faunas and Floras

The assumption that a fauna or flora ends or begins with a formational contact is almost universal, especially where a marine formation is overlain by one of continental orgin, or *vice versa*. A somewhat similar assumption, and equally untenable, is that a fauna or flora preserved at perhaps a single horizon within a formation was coterminous with the lithologic thickness of the formation. Usually, I think, where in the observable rock record a continental succeeds a marine record, or *vice versa*, we must consider the inevitability that the terrestrial forms of animals and plants and the marine forms certainly overlapped in chronology. True enough, every paleontologist will admit the force of these considerations, but when it comes to a practical application to specific problems of correlation, as, for example, the boundary between the Cretaceous and the Tertiary, the disputants all ignore the universal dictum that organisms all have ancestors and all have descendants, unless in some catastrophic way they disappear from the scene without issue.

The idea of guide or index fossils is, on the whole, harmful, especially to the immature student. In some cases certain species fulfill this function admirably. Oftener they do not, and a reliance on such leads to a false faith in what may be untrustworthy, savors of catastrophism and special creation, and ignores the significance of ecological grouping or the relation of fossil assemblages to their environment, the environment being, in my opinion, one of the more important goals of paleontologic research.

The well-nigh universal practice of calling ten or a score of forms a flora or a fauna is much to be deprecated. Vertebrate paleontologists are, perhaps, less open to criticism in this respect than are the students of invertebrates or plants, since both the last two have to consider much larger assemblages. We commonly speak of a marine assemblage as a fauna and are apt to consider it fairly representative if it numbers 75 to 100 species, and yet the number of forms with hard parts suitable

for preservation that make up a normal fauna, at least in post-Paleozoic rocks, numbers several hundred. Such representative fossil assemblages are rare, and whenever found, as in the Saint Cassian beds of the Triassic or the Coon Creek beds of the Upper Cretaceous, they are found to contain many surprises. Nevertheless, we constantly make generalizations and draw far-reaching conclusions from the insufficiency of a few species which we miscall "a fauna." Paleobotanists are even worse offenders.

A normal flora during the age of flowering plants should contain hundreds of forms that might be expected to become fossilized, and if the environment approached tropical they might be numbered by the thousands, and yet our largest known fossil floras, where hair-splitting is not practiced, number in the neighborhood of 500 species. In Martius's Flora Brasiliensis 22,800 species of vascular plants are described, and Wallace has estimated that there are about 80,000 species of existing flowering plants in tropical South America.

Seldom in dealing with terrestrial animals and plants do we have representatives of more than a single ecological group. Perhaps it will be river, or lakeside, or plains—seldom will there be any traces of upland forms, or the smaller forms with more perishable skeletons, or foliage will be missing. Thus the bulk of dinosaur history, like that of the Carboniferous floras, is a history of palustrine environments, and the inhabitants of the more dynamic environments of the uplands have largely failed of preservation.

Like the parable of the talents, however, if we would not be thrown into outer darkness, we must do the best with the talents furnished us, and my picture is not meant to discourage effort, but to reduce dogmatism.

Dispersal

If the chief stimulus to evolution is changing local conditions, why should we have the various habitat races of horses in the Tertiary, or why should any class of vertebrates become modified to all habitats, as, for example, the marsupials in Australia?

Why should the sauropod dinosaurs repeatedly develop into swamp-dwelling forms from arid, open-country types? It seems demonstratable that pressure of population—that is, competition, the old struggle for existence—is a primary factor in dispersal, and that it is also the factor behind adaptation to fossorial, arboreal, aquatic, and all the habitats, as wel as habits, of terrestrial animals. Do weak savage races and weak nations have the least desirable habitats and possessions because they have migrated with such an environment since their origin at some more

favorable center, or is it not because they are not strong enough to obtain and maintain a place in the sun in competition with more advanced races? Philosophically, one can be perfectly logical in holding that the weak races are less advanced, and therefore more primitive, but if changing environment in a single center automatically radiates the more primitive, these same primitive races, in escaping the struggle with more advanced races at a single center, will come into new environments and receive a like environmental stimulus to evolution as the stay-at-homes get from the change of environment in the single region; and it seems to me that this complicates a problem of much complexity to such a degree that it becomes unscientific to make sweeping generalizations. Doubtless at times one, and at times the other, circumstance may prevail, but I can not subscribe to the universality of the proposition that the most primitive members of a stock are farthest removed from their source, despite the imposing array of facts that have been marshaled to its support.

Lithologic Criteria

Everyone is familiar with lithologic similarity as a basis of correlation, and geologists are all aware of the blunders that have resulted, especially in the earlier attempts at correlating North American with European formations, such as, to mention but a few examples, the early correlation of Paleozoic of eastern United States with European Mesozoic (McClure, Eaton), the Rochester shale with the Lias (Eaton), the middle Eocene of Crowleys Ridge in Arkansas with the Potsdam (Owen), the Catskill, Medina, Potsdam, and Newark sandstone with the Old Red sandstone of Scotland (Edwin James, 1821).

It has been assumed that lithologic similarity was really trustworthy within a single basin of sedimentation or stratigraphic province, and out of this idea arose the term homogenesis, advocated by McGee, and the application of this idea was responsible for his greatest mistake—the so-called Lafayette formation.

I recall an earlier discussion before the Geological Society in which an eminent geologist maintained that he could walk for a thousand miles on a single sandstone, and it was therefore of the same age throughout—really proof positive that such was not the case. We now know numerous instances of strongly individualized units—like the Pottsville sandstone, the Austin chalk, the Edwards limestone, the Dakota sandstone, the European chalks, and many others that might be mentioned—that are of different age in different parts of their extent. Within very broad limits, homogenesis is useful. Doubtless in all basins of restricted size

there will be a chronologic relationship in the mineralogical character of the sediments, such as Goldman demonstrated in the sedimentary studies of well sections in the Bend. Such a method is far removed, however, from the hit-and-miss lithology of most all field-work.

More general periods of palustrine conditions, such as prevailed at certain times in the Carboniferous or in our western late Upper Cretaceous, are not without value, and, similarly, widespread continental deposition, with its eolian, channel, floodplain, and swamp deposits, such as so often characterize the emergent phases between marine cycles, may be utilized. I have found that considerable faith may be attached to volcanic ashes in the late Tertiary of the northern half of the Andean region as setting an antecedent date. Elsewhere these would be entirely valueless, and such values are always the result of experience and derived from other criteria, and lack any original intrinsic value.

Since invertebrate paleontology must remain the basis of geologic classification, and, despite their greater value, terrestrial vertebrate and plant fossils will presumably always have fewer cultivators and more limited application, it results that the exact agreement of independent conclusions from these three fields of endeavor can not be hoped for.

The remains of terrestrial animals and plants are found chiefly during those times near the boundaries of the periods as based on marine life, or actually bridging the intervals between marine cycles. There will, therefore, be less change in the facies of the terrestrial life from late Jurassic to early Lower Cretaceous (the so-called Wealden problem), or from late Upper Cretaceous to Tertiary (the so-called Laramie problem), from Devonian to Carboniferous, or from Triassic to Jurassic (Rhætic problem).

The statistical method of comparing faunas and floras has about as few advocates at the present time as has the classical method of determining the subdivisions of the Tertiary by the percentages of still existing species which they contain, and therefore need not be discussed, since to an unreliable method is added a large personal equation.

There has been much discussion of the relative value to be placed on the commoner forms as opposed to the rarer forms, or the older types as against the prenuntial types. It is probably true that, for most stratigraphic purposes, in a transgression of the sea, marine forms migrate as a body with the invading waters, but it may be doubted whether the resulting good lithologic boundary, backed as it may be by a faunal assemblage, constitutes a chronologic boundary throughout its whole extent.

In fact, if one takes the trouble to assemble them, there are hosts of

examples of proven cases where the lithologic unit, with its characteristic fauna or flora, differs in the age of its limits throughout its whole extent except parallel to the coastline of advance of the waters in which it was deposited.

Facies Faunas and Floras

Both Elles[6] and Stamp[7] in recent discussions have minimized the significance of the usual type of facies fauna of transgressing seas and have emphasized the idea that incoming new species, to be of real value, should not be those that reflect the environment (lithologic)—that is, not a facies fauna—but should be evolutionary products from the deeper waters of shelf seas, where the environment was more stable.

Undoubtedly the greatest diversity of environments is to be found close to the strand, where also slight changes in sealevel are most effectively felt, and these regions are, moreover, the usual paths of dispersal. This conclusion is the reverse of that enunciated by Ulrich (1916), that there is no ground for the belief that expanding epicontinental seas were centers of evolution, which occurred in the ocean basins. It seems that observational data make the former more likely.

Hence it would seem that evolution should proceed more rapidly in the epicontinental seas than in the relatively stable environments of deeper waters along the continental shelves. A common dictum of historical geology asserts that evolution is most active among terrestrial organisms when land areas are restricted—that is, during continental submergence—and that it is most active among marine organisms when water areas are restricted—that is, during continental emergence.

There is little basis, in fact, for believing that the effect in an area the size of a continent will be homologous with that in an island, or that the area of a continental shelf can be logically compared with that of a partially enclosed basin. At least, the implied idea of crowding and the implied intensification of the struggle for existence is not the explanation any more than are transgressions of the sea to be explained by the water displacement of the products of erosion that are carried down to the sea.

That continental emergence and submergence are important factors in evolution, I believe most heartily; but their action is not that due to restriction or expansion of area, with concomitant increase or surcease of competition, but is almost, if not entirely, due to the environmental

[6] G. Elles: Evolutional paleontology in relation to the lower Paleozoic rocks. Rept. Brit. Assn. Liverpool, 1923, pp. 83–107.

[7] L. Dudley Stamp: Geol. Mag., vol. 61, August, 1924, pp. 351-355.

changes brought about, and which may be roughly grouped as climatic—that is, changes in wind and oceanic circulation, resulting in changes in temperature, humidity, rainfall, etcetera. In fact, such changes in the relative proportions of land and water, combined with the altitude and geographic pattern, are the major factors governing climate throughout geological history.

Faunas of epicontinental seas must have of necessity been subject to far greater degrees of change than those of shelf seas or particularly those of the open basins.

The work of all biological stations shows that all marine organisms exist as ecological groups or communities under certain more or less constant physical and organic environments. The more important of these are temperature, salinity, and clearness of the water, the last generally correlated with the character of the bottom.

Depth becomes a factor merely as it is related to temperature, light, quietness of water, etcetera. In shallow water the facies of the organic assemblage varies greatly, according as the bottom is hard or soft, muddy, stony, or sandy. Unless the past was very different from the present, with a wonderful extent of uniform environments, or a large proportion of the life forms were less susceptible to differences in environments, we should expect to observe similar changes of facies in contemporaneous fossil faunas. This is the basis for the belief among paleontologists in the value of general—that is, generic—rather than particular—that is, specific—resemblances as a basis for correlation.

Ulrich considers this criterion to be of little value in stratigraphy, and contends that the character of the matrix bears no definite relation to the kinds of organic remains contained in it. "Not only the same classes and genera, but often the same species, are equally abundant, whether the rock is a limestone, a shale, or a sandstone" (Ord.-Sil. boundary, page 601). This is explained as due to the time involved in sedimentation, during which local conditions shifted back and forth, and to the rearrangement of dead shells by waves, currents, etcetera.

That is, as regards environments, a fossil fauna is a composite. This is doubtless sometimes the case; but it is difficult to believe in the universality of application of such a statement, in the light of the numerous facies faunas that have been described, especially in the European Jurassic. The modern English paleontologists seem to have no difficulty in recognizing facies faunas in the Paleozoic; and that this can be done in North America is shown by Twenhofel's work on the Anticosti faunas, or that of McLearn on the Arisaig faunas. That there is usually a cor-

relation observable between lithology and fossil content may be verified by anyone who will look at the Miocene section at Yorktown, Virginia, or that along the Calvert Cliffs in Maryland. Nothing I have seen is more convincing in this respect than the Devonian shale fauna in the Andes, where one may go for hundreds of miles without seeing a normal Devonian assemblage of life and where the hard and soft bottom faunas are startingly distinct, though believed to be contemporaneous.

The question of the recognition of environmental facies in marine faunas leads naturally to a brief consideration of overlaps.

The more recent recognition of the many overlaps and breaks in the sedimentary record of North America is a noteworthy achievement and will doubtless in the future still further augment our conception of the duration of geologic time, but it seems to me that a word of caution is not amiss. Where an adequate fauna from a predicatable source can be obtained, such evidence of overlap may be entirely convincing. Where the "fauna" is small and its source hypothetical, one may well fall back on the belief that the observed conditions may not be those of an overlap, but simply a shift of environments, such as have been frequently described. Shifting environments are well illustrated in Bowen's and Stebinger's work on the Upper Cretaceous of Montana. They are similarly shown in the Colorado Upper Cretaceous of Alberta. Many illustrations might be drawn from foreign fields, in which that of Leriche on the Eocene of the Paris basin is among the most clear-cut and convincing. In fact, I know of no work in which overlaps and facies faunas due to shifting environments are more clearly recognized and depicted than in that of the modern students of the Paris basin.

A rather clear example of shifting environments in this country, although not adequately described in print, is furnished by the so-called Comanche series of the western Gulf region, where, in some cases, each lithology has a recognizable fauna, and where, in other cases, certain dominant species cut across the lithology and show that it is possible to recognize the time element in lithologic units which are progressively younger in one direction. Transgressions may be relatively rapid, but the time element involved can not, in my opinion, be ignored.

Non-selective Characters

The importance of discriminating minute differences, particularly in forms of some structural complexity, and the placing of much reliance on similar mutations for purposes of correlation has been repeatedly urged by Ulrich and is undoubtedly of the greatest value. These must,

however, be in the same sharply defined species, variety, or mutation, and such value is not to be attached to such features as relative proportions, septal or crural characters in brachiopods, glabellar or pygidial modifications in trilobites, etcetera, unless these are in a genetical series.

That minute mutations should be biologically unimportant to be of greatest value seems to be a doubtful proposition. In the case of the Mollusca, as first pointed out by Dall, apparently unessential features, as, for example, minor shell ornamentation, tend to be persistent and non-evolutionary over periods of time as long as from the Cretaceous to the present.

The same is true to a much greater degree in plant foliage, which experience shows to be one of the most conservative parts of the whole plant organism. Foliar form is much slower to change than floral and fruiting parts, or than anatomical structures, although botanists are somewhat backward in admitting this, and our current taxonomic scheme is still largely based upon floral morphology as it was in the days of Linnæus.

The ginkgos and cycadophytes furnish the most impressive illustration of this foliar conservatism. The former remain practically unchanged from Devonian to Recent. In the cycadophytes, where other organs than leaves are much better known than in the case of the ginkgos, we see foliar types persisting with scarcely a modification from Carboniferous to Recent, during which time the stem anatomy varied widely and the floral organization underwent the most remarkable and varied rearrangement.

Another thought which I have long had in mind and which would be more properly presented before biologists, but which has some interest for us in connection with what has been called biologically unimportant characters, is this: We have been so completely dominated, especially in paleontology, with the Darwinian idea that every feature or organ of an organism was useful—that is, adaptive—or was inherited from an ancestor in which it was useful, even if that use had disappeared in the descendants, that we have entirely lost sight of the idea that a feature might be entirely useless in the Darwinian sense and be simply the result of what for the lack of a better name might be called the formative process—that is, the physical-chemical reactions governing development and growth. Certainly, from the historical point of view, structures antedate functions.

Both the terms biologically unimportant or useless savor of a knowledge that we do not possess. What seems to me a better term, although

still open to some objection, is *characters without survival*—that is, without *adaptive value*. The meaning of this is, I think, obvious. It does not mean that such characters will necessarily be evanescent; for, as I have stated, I regard such characters of small or no survival value, those outside of natural selection, as being extraordinarily persistent through long periods of time. Such will, then, lack the special chronologic value that is so important for precise correlation, and only those which are of selective value will furnish data of precision for correlation, although the others will be of great importance for purposes of identification of species and genera.

Stage of Evolution

We hear much of the chronologic value of the stage of evolution as shown by the pattern of a mammalian tooth, or the sutures of an ammonite shell, or the septa of a corallum, or the brachidium of a brachiopod.

In the past much of this has been subjective. Where we can be sure that we are dealing with a genetic series, either a gens (species group) or a natural genus, as opposed to a composite genus, nothing can be more trustworthy. Many, perhaps the majority, of the genera of fossil invertebrates do not rest on this secure basis, however, and Bather in 1920 pointed out the necessity of getting genetic lines before we could be sure that our genera were not polyphyletic. Such genetic studies as those of Kiaer on the brachiopods, Elles on the graptolites, Land, Carruthers, and others on corals, Smith on the ammonites, and Ulrich on the ostracods need to be greatly multiplied and to find more imitators in this country if we are to rise above mere descriptive work.

Probably no group has been as intensively studied, from an evolutionary point of view, as the Ammonites, and the veriest tyro among geologists knows that the Goniatite type characterizes the Paleozoic, the Ceratite type the Triassic, and the Ammonite type the post-Triassic Mesozoic. What he probably does not know is that certain genetic series may by acceleration reach the post-Triassic stage in the Permian (*Waagenoceras*), or that the degree of this acceleration, which may affect the whole shell or only certain parts, or of arrestation, or retardation, in the different stocks, give us wide departure from the predicated norm, as, for example, the combination of acceleration and subsequent arrestation that gives us the Pseudoceratites of the Cretaceous.

A similar difficulty is present in all other groups, as Elles has shown most strikingly in the change in attitude, reduction of branching, and elaboration of the theca in the graptolites. This is probably just as

true in the case of a tooth or a trilobite, for evolution is neither rhythmical nor synchronous in separately evolving lines, so that confusion is only worse confounded unless we are dealing with genetic lines.

I have not attempted to discuss such long known and more or less illusory criteria as the continuity of lithologic or paleontologic expression or of superposition (succession), or the criteria based upon unconformable or disconformable contacts, which may vary chronologically from locality to locality, as do all diastrophic criteria; nor has it seemed worth while to more than mention such unreliable features as degree of lithification or regional metamorphism.

Summary

I have touched upon many aspects of the problem rather briefly, since a fully documented and illustrated discussion would be much too long for an occasion of this sort. If what I have said shall inspire caution in generalization and diminish dogmatism, or awaken ambition to do fundamental work in the minds of many of our budding paleontologists, I shall feel amply repaid for the effort required to criticize many of our cherished traditions and prejudices—the two are synonymous.

It may seem that the bulk of my comments are more in the nature of destructive criticism than of constructive effort. This is only too true, but they may prove of value, nevertheless, to those who are inclined to accept too whole-heartedly one or the other of the criteria of correlation. In my opinion, some of these roads to correlation should be marked "No thoroughfare"; others, "Under construction; travel at your own risk," and none, I fear, are entitled to be considered first-class roads, in good condition for travel.

The history of the efforts at the formulation of criteria has always been that each new suggestion was hailed as having wide application, to be followed by increasing doubt as observations accumulated. This should be a stimulus to increased effort, and although there is no single or royal road to certainty in matters of correlation, I may close by reiterating what I stated at the beginning, that, in my judgment, the evidence derived from paleontology in its broader applications furnishes the most reliable, even though imperfect, basis for correlation that has been discovered.

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MARINE AND TERRESTRIAL CONGLOMERATES[1]

BY THE LATE JOSEPH BARRELL[2]

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[1] Manuscript received by the Secretary of the Society January 20, 1925.

[2] In connection with a lecture course on the processes of sedimentation, given annually to graduate students in Yale University, Professor Barrell was led to study the various kinds of conglomerates and the ways of their making. The gist of his results along these lines he presented on December 29, 1908, at the Baltimore meeting of the Geological Society of America. A half-page summary of this paper was published in the Society's Bulletin for 1910 (volume 20, page 620). A long paper had, however, been completed before the meeting, but Barrell was not satisfied with it, since he wanted to make further quantitative measurements. A second draft was finished in August, 1910, but even though Barrell did not pass away until May 4, 1919, he never found the time to review his manuscript and get it ready for the printer. This has now been done by his literary executor.

The entire study has been divided into four parts, three of which appear here. The last one, on "The nature and environment of the Lower Cambrian sediments of the southern Appalachians," which was an application of his theories to an actual series of formations containing great thicknesses of conglomerates, was printed in an earlier number of the *American Journal of Science* (January, 1925). The remaining, less complete, sections have been carefully studied, the duplicate matter eliminated, and the whole brought into the sequence indicated in the second draft.—CHARLES SCHUCHERT.

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Introduction

The older interpretation of all sedimentary rocks as marine unless they contain organic evidences of continental origin, and of all continental formations as having formed under estuarine or lacustrine conditions, is no longer adhered to by geologists. Although the greater portion of the sedimentary rocks have originated beneath the sea, yet the origin of any particular formation devoid of fossils must now be regarded as an independent problem. This newer attitude has come about through the recognition of the great value of physiography in the correct interpretation of geologic deposits. From different parts of the world a great mass of data has been accumulated, and viewed in different ways, according as each worker was most impressed with the results of river, ocean, desert, or ice.

Conglomerates may be accumulated and laid down as subaqueous deposits beneath permanent water bodies, as the result of wave action on rocky or gravelly shores. They may also form on land, as the result of rain and river action, when the relief is sufficient to cause movement of the coarser land waste and there is enough rainfall to provide the moving power. Conglomeratic materials, being the coarsest products of erosion, are moved shorter distances from the regions of erosion and are limited to narrower zones of deposition than sand, clay, or matter in solution. The shifting location of gravels is, therefore, a sensitive recorder of changes either in the strand-line, in land relief, or in climate.

According to the place of accumulation, whether above or below the surface of permanent water bodies, conglomerates are either subaqueous or terrestrial. The former include, in addition to the normal type, such special subdivisions as (1) intraformational conglomerates, made by

wave action along shores that are periodically exposed for a more or less long time (not tidal flats), or in very shallow water, but not necessarily near the shore; (2) iceberg, or glacial, conglomerates, deposited beneath water without opportunity for wave action; (3) estuarine conglomerates, made in arms of the sea protected from the more violent waves; and (4) lacustrine conglomerates, originating on the shores of lakes. Such special forms as intraformational conglomerates and subaqueous glacial deposits are readily recognized and separated from those produced through shore action and need not be further considered. Although lake deposits are classed as continental rather than marine, the beach deposits of lakes differ only in degree and not in kind from those made on the shores of the open ocean. For the present purpose, therefore, the shore deposits of lakes, estuaries, and oceans are treated together and classed as marine.

Terrestrial conglomerates are due to the cooperation of tectonic and climatic factors whose relative import may or may not be determinable. They may be said to include such special kinds as fragments in residual earths, talus heaps, and glacial deposits. Such special forms, however, are readily recognized and need not be considered in the present connection. Hence under terrestrial conglomerates will be treated only those gravelly deposits which have been moved horizontally and accumulated through rain and river action.

Part I. Relative Production of Gravel through Littoral and Fluviatile Erosion

Present rates of erosion

General statement.—The relative quantities of gravel resulting from marine planation and subaerial erosion depend, first, on the total volumes of rock waste eroded by these two agencies at the present time, and, secondly, on the proportion of this waste which enters the transportation system as gravel. The ratio of gravel to total waste produced must be determined, however, not only for the present exceptionally emerged and high continental surfaces, but for the highly variable geologic past as well.

The character and quantity of the rock waste produced by gravel denudation must have been highly variable throughout geologic time, and it is, therefore, as important to determine the influence of the causes of this variation as it is to calculate the present rates of denudation.

Marine denudation.—The east and south coasts of England are doubtless the best studied shorelines in the world, their records extending back 500 to 1,000 years. According to estimates, much of this coast

shows an average advance of the sea of from 1 to 2 yards per year. This is, however, against soft formations, and the cutting is excessive because of a rise in the relative level of the sea of from 20 to 60 feet, estimated to have taken place about 4,000 years ago.

Geikie points out that along the rocky western coast of England and Wales the erosion is perhaps less than one foot per century. For purposes of computation, he therefore assumes a rate of marine erosion of 10 feet per century, an estimate which he thinks attributes to the waves a much higher rate of erosion than can probably be claimed for them on the average.[3] De Lapparent accepts this estimate, and, by assuming an average cliff height of 50 meters and the coastline of the world as 260,000 kilometers (161,600 English miles), he obtains 0.3 cubic kilometer (.07 cubic mile) per year as the total volume of marine denudation.[4] However, both Geikie and De Lapparent consider that 10 feet per century is probably too great for the world's coastline. De Lapparent, moreover, takes the coastline as 161,000 miles, but this length is reduced to 125,000 miles if minor indentations be omitted. Further, he takes 50 meters (164 feet) as the average height of the cut; but, considering the vast areas of low coast, this again seems a high rather than an average figure, even allowing 30 feet for submarine erosion in continued marine planation. By using the lower values of these three factors, a value for marine planation for the world is found to be of the order of magnitude of between 0.02 and 0.10 cubic mile per year.

Fluviatile denudation.—From the present discussion of subaerial denudation are eliminated all gravel or boulders which originate from eolian or glacial action, except in so far as this waste is fed into rivers. Even so, a fairly accurate value of present fluviatile denudation can not be given until precise investigations similar to those attained for a few river basins are at hand for the whole globe. Moreover, fluctuations in the rate during the geologic past are uncertain. Nevertheless, the estimates for fluviatile denudation are much more precise than those for the marine type, and are, accordingly, sufficiently close for geological application.

Several more or less independent estimates may be given in order to show the comparative reliability of the results. As Croll first pointed out, the sediment discharged by the Mississippi may be used as an average for the earth, since it embraces a large area possessing sufficient variation in climate and topography to make it fairly representative of the whole land surface other than deserts. Estimates of the average rate of

[3] A. Geikie: Textbook of Geology, 4th ed., 1903, p. 593.
[4] A. de Lapparent: Traité de géologie, 4th ed., vol. i, 1900, pp. 242, 243.

denudation for the Mississippi basin, which include both dissolved and mechanical sediments, vary from one foot in 3,000 years to one foot in 5,200 years. Taking 44,000,000 square miles as the area of the land draining into the oceans and one foot in 4,000 years as the average rate of fluvial denudation, it appears that 2.1 cubic miles of land sediment each year is moved into the sea.

A more detailed analysis is based on the amount of sediment carried by sixteen rivers, which leads Penck to conclude that somewhat more than 10 cubic kilometers (2.4 cubic miles) of rock is annually moved by the rivers to the sea. Taking into consideration the whole land surface, this would give a yearly erosion of 0.08 millimeter; but Penck justly remarks that this does not give a true average, because large quantities of river sediment are carried to interior basins and other portions are laid down in lakes and on floodplains. How great these quantities are, his data naturally do not give the means of ascertaining, but he thinks that the minimum valuation may, perhaps, be equal to the amount of sediment carried to the sea. It is to be concluded, therefore, that the sum of fluviatile denudation is at least 20 cubic kilometers (4.8 cubic miles) per year—an estimate that is, however, based on rivers which drain about one-quarter of the land surface.[5]

Besides the statements cited by Penck as a basis for calculating the large quantity of land-stored river waste, it should be mentioned that the Nile deposits annually upon its delta 24,400,000 cubic meters of silt and takes to the sea 36,600,000 cubic meters of the same kind of material.[6]

Prestage, in 1861, made careful simultaneous measurements on the silt in suspension in the Matabangah (one of the distributaries of the Ganges), first on leaving the Ganges and again nearly at its junction with the Hoogly. He found that two-thirds had been deposited *en route* in not much over 50 miles, measured in a straight line.[7] Not only, however, is much land waste deposited upon delta surfaces, but it is to be noted also that enormous amounts are now accumulating on piedmont slopes and in inland basins on the eastern slopes of the Andes, and especially on the northern slopes of the great Asiatic mountain systems.

In order to prevent undue confidence in these estimates of fluviatile denudation, it is doubtless best to state probable limits rather than definite figures. Having regard for other, but apparently less reliable, estimates, it may be said that the rivers move into the sea per year between 1.5 and 3.0 cubic miles of rock waste of a specific gravity of 2.7.

[5] A. Penck: Morphologie der Erdoberfläche, vol. 1, 1894, pp. 379-385.

[6] A. Geikie: Op. cit., p. 515.

[7] James Ferguson: On recent changes in the delta of the Ganges. Quart. Jour. Geol. Soc., London, vol. 19, 1863, pp. 350, 351.

As deposited, however, the specific gravity will be less, that of the mud averaging 1.9. On the other hand, the total volume of fluviatile denudation is estimated to be between 3.0 and 6.0 cubic miles per year.

The results thus far obtained on the rates of denudation by the sea and the rivers of today may be tabulated as follows:

Present Rates of Denudation

	Volume eroded per year in cubic miles.
Marine denudation	.02 to .10
Fluviatile denudation:	
As marine deposits	1.50 to 3.00
As continental deposits	1.50 to 3.00
Total erosion	3.02 to 6.10

FLUCTUATIONS IN RATES OF EROSION

The determination of the present ratio of marine to subaerial denudation is, however, but the first step towards ascertaining their relative importance through geologic time. The ratio of land and sea has varied widely and the periodic increase of epicontinental seas has at times greatly extended the coastline. Vertical movements have also modified repeatedly the power of erosion, and, finally, variations in climate, by controlling the mechanical power of the waves and rivers and the chemical decay of rocks, have also played their part.

In marine denudation the influence of the size of the landmass is the first factor to be considered. With islands of similar form, but of variable dimensions, the coastline varies directly as the diameter, whereas the area varies as the square of the diameter. Consequently, other things being equal, the ratio of marine to subaerial denudation varies inversely as the diameter of the landmass. In Great Britain, with an average elevation of 650 feet and surrounded by shallow seas, estimates given by Geikie show that marine and subaerial denudation are of the same order of magnitude.[8] In smaller islands, such as Heligoland, marine denudation is far more dominant.

The next factor to be considered is the influence of oscillations of the strand-line. Such movements are intermittent and comparatively rapid, and where they attain the depth of marked wave action, from 30 to 60 feet, they bring the sea into new relations with the land and give rise to highly accentuated erosion. When a physiographically mature land is elevated to less than the depth of the submerged portions of the continents, there results a negative movement of the strand, the sea is shal-

[8] A. Geikie: Op. cit., pp. 591, 593.

lowed and brought to work against a gently shelving slope. The incoherent materials of the previous sea-bottom may be rapidly rehandled, but these, as banks and bars, tend to protect the solid land, with the result that the change does not lead to an increased rate of marine denudation.

On the other hand, a vertical uplift of sealevel of 30 feet or more decidedly increases marine denudation, since it brings free wave action against the slopes of a stream-dissected land. The power of the sea is then concentrated on the more exposed portions of the coast, which crumble before its assaults.

The shoreline through geologic times was an ever-shifting one, oscillating in unequal rhythms over wide areas, the negative movements inaugurating new cycles of erosion, the positive ones characterizing the succeeding epochs of earth repose. The rate of marine to subaerial denudation has, therefore, varied largely and frequently in the same region during geologic time. Applying these considerations to the ratio previously derived, it is to be noted that the continents as a whole since the close of the Miocene have been elevated to a degree unknown since Proterozoic time. Vast interior tracts are now elevated hundreds and even thousands of feet above the sea and are mantled by strata that are being subjected to decided erosion. This does not, of course, imply that more ancient plateaus and mountain ranges have not been built and destroyed, but it apparently does indicate that at no time since the Proterozoic has the earth witnessed such a deep withdrawal of the sea. Accordingly, the lowering of the ultimate baselevel, together with the great orogenic and epeirogenic movements of the Pliocene and Pleistocene, has stimulated subaerial denudation to a degree previously unknown.

Considerable of the limestone of the Paleozoic and Mesozoic eras may have come from the erosion of Gondwana and the Old Northland, but in a discussion relating to mechanical sediments we must deal with the existing continents. Their average elevation is now about 2,250 feet, their area 55,000,000 square miles. In the geologic past a reasonable estimate might assign 1,000 feet as an average height for these lands, and their area may have been 75 per cent of the present. At times their height above the sea has certainly been lower and their emerged area smaller. The shoreline, however, through the marked invasion of the continents by epicontinental seas, would be actually greater in length than at present.

The rate of subaerial denudation may be assumed as roughly varying with the square of the average elevation, but a moderate diminution in area through the invasion of interior seas would not diminish subaerial denudation in direct proportion to the area covered, since their sediments

may come to rest below sealevel, where otherwise a larger proportion might be stored as deposits upon the land. Taking into consideration, then, only the variations in the present average height of the continents, it may be said that the total value of subaerial denudation has often been not over one-fourth, and may at times have been only one-tenth, of its present value.

The other side of this problem of oscillating strand-lines is concerned with the rate of marine denudation in relation to the length of the shoreline. This rate is increased, it is true, by the lengthening of the shoreline due to the spread of the inland seas, but over against this must be placed the reduced power of wave action because of the narrowness of these seas. If, in addition, the waters are shallow, and especially if their depth is less than 100 feet, the waves would spend their force partly upon the bottoms rather than upon the margins of the seas.

The rate of marine denudation is further subject to very considerable change, depending upon the direction of movement of the strand-line, minor oscillations of level for a limited time greatly affecting the power of the sea. England is a case in point. At a period from 3,500 to 4,000 years ago a rapid subsidence took place to an average depth of, perhaps, 50 feet, by which the sea was brought to bear with fresh power against the more recent and less resistant geological formations. An abnormally high local rate of marine denudation has been the result, but eventually, when the shoreline has attained maturity, the waves can strike the shore only after passing over a wide submarine platform. Therefore this abnormal present rate can not be taken as the basis for computing the total annual volume of marine denudation for the world.

Although the average trend in the movement of the present strand-line is, perhaps, still open to question, it is probably, on the whole, a negative phase; the present shores are dominantly emerged, as may be seen on Map 4 of Andree's *Handatlas*.

In conclusion, it may be said that marine denudation has attained its highest absolute and relative value at times of great marine transgressions accompanying and following periods of prolonged quiet and baseleveling. Its absolute value may readily have been twice the present amount, and its value relative to subaerial denudation may have attained even twenty times the present ratio, possibly bringing the two modes of erosion appreciably nearer together, though still far from equality when the totality of erosion is considered.

AMOUNT OF GRAVEL PRODUCED BY EROSION

Influence of composition and structure.—Variations in rock formation, in the attitude of the land, and in climate exert such a profound influence

upon the nature of the products of erosion that no close estimates can be made. It is important, however, in a comparison of gravel formations of marine and terrestrial origin, that there should be some discussion of the factors which operate in the two cases.

Unconsolidated formations are resolved by erosion into their original particles, and where such deposits contain gravel it will be redeposited in the sea as conglomerates. The question, therefore, rises as to how much of these conglomerates may be reworked river gravels. In so far as the rivers bring gravel to their deltas, or the sea invades them, there is thus given an opportunity for the making of marine conglomerates that did not arise through erosion of the sea. The answer is that but a small proportion of river gravels can thus be made over into marine conglomerates, because gravels are commonly deposited inland in the middle portions of the river courses.

Gravels of the smaller streams, such as flow from young mountains in the vicinity of the sea, are commonly deposited upon a grade of as much as 5 feet per mile—frequently higher—and thus a part of the gravel builds a subaerial piedmont slope. It is, therefore, only the river gravels within the reach of the sea that may become important sources of marine conglomerates.

For the seacoast of England, Douglas estimates that chalk may furnish but 5 per cent of foreshore material, the remainder being swept into deeper water. Glacial formations probably yield 30 per cent; but where the detritus is of granite, practically the whole goes into foreshore material.[9]

For many kinds of rock the inherent structure is of fundamental importance in determining the size of the detritus. A closely jointed or fissile rock will supply many fragments capable of being handled by the agencies of erosion. A massive rock, on the other hand, yielding fragments too large to be directly handled, may require assistance through the friction of pebbles and sand. Such wear, as Daubrée has shown, tends to produce mud and very fine sand until the fragments have been reduced to a size which the erosive agency can move.[10] His experiments also showed that, even in the presence of violent shocks comparable to those given by the most rapid waves, fragments of granite did not break up into smaller ones, but, on the contrary, were pulverized. Consequently, an inherent structure which permits a rock to break into numerous small but resistant fragments is highly favorable for the production of large quantities of gravel.

[9] W. T. Douglas: Minutes of evidence, Royal Commission on Coast Erosion, vol. I, pt. i, p. 181. Wyman and Sons, London, 1907.

[10] G. A. Daubrée: Géologie expérimentale, vol. I, 1879, pp. 250-253.

Relative importance of subaerial and subaqueous erosion.—The conclusion of Daubrée is only true within limits, as is shown by the force of impact of stone upon stone in moving water. Further light is thrown upon the subject by the experiments of Edward Erdmann, who placed rock fragments in a tilting trough.[11] The number of tilts multiplied by the length of the trough gave the distance traveled by the fragments. His results warrant the republication of his tables, especially as they apparently have not been heretofore published in English.

Erdmann's Experiments

	Number of stones at start of investigation.	Mean weight of individual stones.	Mean weight lost per stone for each kilometer traveled.	Number of pebbles at end of investigation.	*Per cent of weight lost by all stones in whole distance.	*Per cent of increase in number of stones in whole distance.
First investigation with angular fragments; total distance traveled, 6.88 kilometers						
		Grams.	Per cent.			
Granite	57	36.54	0.30	60	2.1	5.3
Orthoceras limestone	50	61.22	1.29	72	8.9	22.0
Granular limestone	68	40.01	0.92	77	6.3	13.2
Cambrian sandstone	50	26.36	0.72	53	5.0	6.0
Rhætic sandstone	42	40.48	5.85	..	40.2	...
Argillaceous schist	45	24.55	1.59	56	11.0	24.4
Second investigation with the previously rolled fragments; total distance traveled, 13.54 kilometers						
Granite	45	28.33	0.42	47	5.7	4.4
Orthoceras limestone	51	26.18	1.83	66	24.8	29.8
Granular limestone	51	24.43	1.43	54	19.4	5.9
Cambrian sandstone	29	21.24	0.75	30	10.1	3.4
Rhætic sandstone	25	13.96	7.38	..	100.0	...
Argillaceous schist	40	11.38	3.16	52	42.8	30.0

	Mean weight in grams, about.	Total distance of travel in kilometers for complete destruction of fragments.
Granite	36	278
Orthoceras limestone	61	64
Granular limestone	40	85
Rhætic sandstone	40	15
Argillaceous schist	24	42

[11] E. Erdmann: Bidrag till kännedomen om rullstenars bildande. Geol. Föreningens Förh., Stockholm, vol. 4, 1879, p. 407; also A. Penck: Morphologie der Erdoberfläche, vol. I, 1894, p. 293.

* Column added by Joseph Barrell.

Erdmann's results indicate that, for the velocities used, the angular fragments of the harder rocks increased in number during the first experiment somewhat faster than the loss of weight; but that, in traveling a second distance twice as long as the first, the increase in the number of pebbles was actually less than in the first instance, although the loss in weight was proportional to the distance and hence about twice as great. With the weaker rocks the fragmentation of the angular pieces was at first considerably faster than the loss by weight, but in the second experiment the loss of weight to individual pebbles by grinding and by fracture was nearly equal.

For a given velocity of impact, the tendency to fracture will vary directly with the diameter of the pebbles, because the fracture surface varies as the square of the diameter, whereas the mass of the stone varies as the cube. The tendency to fracture will also be favored by angularity of pebbles, permitting corners to be spalled off. It is seen, therefore, that the larger fragments handled by waves or mountain streams will be speedily smashed down to a smaller size by subaqueous impact, but if they can not be freely handled and must be reduced by the impact of smaller material, the result is a wear rather than a fragmentation. If the pebbles in a stream or in surf were of one size, down to a certain limit the gravel would decrease in fineness and be carried to greater distances without decreasing markedly in volume; but, as a great amount of smaller pebbles and of sand is usually also present in the initial waste, a proportionally greater part of the wear of the larger fragments is due to abrasion by the finer material. Consequently, further investigation along the lines of Erdmann would determine a limit to, rather than an average of, the effects produced in natural streams.

From these facts it is seen that the bedrock on which the water works is destroyed by abrasion rather than by direct impact of material moving across it. Even if impact were possible to the extent that one loose stone might strike another, the fact that the bedrock is part of an extended surface would result in some pulverization rather than a fracture. The actual cut made vertically on the stream bed or horizontally at the strand-line, though made by gravel, does not yield gravel. The effect of water currents is rather to wear out the gravel, though at an early stage in the process a diminution in the size of the pebbles supplied to the mill may proceed somewhat faster than the diminution in total volume. This can only mean that gravel is chiefly produced subaerially.

In marine denudation, as Whitaker was the first to show,[12] the action

[12] W. Whitaker: On subaërial denudation and on cliffs and escarpments of the Chalk and the Lower Tertiary beds. Geol. Mag., vol. 4, 1867, pp. 488-493.

of the sea is largely assisted by subaerial forces, which serve to weather back the sea-cliff and feed its broken materials to the sea. Accordingly, the strictly subaqueous work is confined to the pushing to and fro of material over the rock platform. This erosion on an exposed shore is fairly vigorous to a depth of about 5 fathoms, but must proceed with decreased force to depths as great as wave base, provided, however, the bottom slopes out to deeper water, so that the fine waste may be removed as fast as produced.

Taking De Lapparent's estimate of an average cut by the sea as 50 meters, this means that 60 to 80 per cent of the material supplied by marine denudation is capable of yielding gravel, other conditions being favorable.[13]

In active fluviatile erosion, on the other hand, the results of actual corrasion on the bed of streams are insignificant in volume in comparison with the subaerial waste fed into a river system through gravitative creep and pluvial wash. The ratio of the two is given approximately by comparison of the area of stream channels flowing on rock bottom in time of flood to the total area of the river basin. The more largely subaerial character of fluviatile erosion favors, therefore, a somewhat greater production of conglomeratic material per equal volume eroded than is the case with marine denudation. It is a less important factor, however, than the others which enter into the problem.

Mechanical and chemical factors in production of gravel.—Mechanical weathering or rock disintegration operates through the action of unequal expansion and contraction of the mass, the alternate freezing and thawing of included water, and the corrasion by moving ice, water, and wind. It is the disrupting, rather than the abrading, agents which are here especially concerned in the making of gravel, although glacial action, by plucking loosened fragments from the rock-floor and crushing boulders to a size which running water may move, furnishes a large amount of coarse waste which may later enter into aqueous conglomerates. The vigor of the disrupting agencies increases with the declivity, since gravity removes coarse waste with facility from steep slopes and maintains conditions suitable for rapid attack. On flat surfaces, however, the rock becomes protected by a mantle of waste which must be broken to smaller sizes before currents of water or wind may operate.

A moderate degree of chemical activity resulting in rock decomposition also facilitates the work of the disintegrating agencies in breaking up rocks into material for gravel. The chemical action of water with

[13] This matter is also discussed by D. W. Johnson in "Shore processes and shoreline development," 1919; see chapter ii, The work of waves, and chapter iii, Current action.

its dissolved gases works along the joint planes at depths beyond the reach of sun and frost action. It works selectively on the more easily permeable and decomposable strata, and thus aids in destroying the cohesive unity of the rock-mass. A dominance of chemical activity, however, by destroying the cementation of the rock and breaking down the decomposable minerals, greatly lessens the quantity of material which is capable of forming gravel. There are, of course, exceptions, as in limestones and conglomerates consisting of siliceous pebbles bound by a weak cement. In such formations chemical activity may give rise to gravelly material on flat slopes at a faster rate than the mechanical forces of disintegration could work under similar slopes.

Relative quantities of marine and fluviatile gravel.—Applying the principles discussed in the previous pages to the conditions of marine and fluviatile denudation, it is seen that the former favors much higher declivities than the latter, for the sea works horizontally and tends to undercut the land, while the rivers cut vertically.

In regions with humid and non-arctic climates, unless they are undergoing extremely rapid fluviatile erosion, the stream slopes are gentle. The surface is here covered with soil held by vegetation, which prevents the exposure of the rocks to the mechanical forces. Over such broad tracts gravel can be made only from the most resistant materials—vein quartz, chert, conglomerates, and quartzites. Such may be estimated at not over 5 per cent of the rock-masses. In high mountains, however, disintegrating forces work at a maximum, and under favorable conditions frost action very rapidly supplies coarse waste, which may move on a comparatively gentle gradient, as is shown by the stone rivers of subpolar climates. In semiarid regions the vegetation does not hold the products of rock destruction, and the water action, though intermittent, is very powerful. Over such regions the steeper declivities due to marine erosion result in coarser waste, but do not give a proportionally greater advantage in amount of gravelly waste produced. As has been shown, the subaqueous reduction of coarse waste by streams to a size at which it can be transported to regions of deposition is chiefly by a wearing down rather than a breaking up of the coarse into finer material.

The advantage of declivity which is possessed by the sea margin may be regarded as further offset by the fact that the sea works to a large extent on superficial and unconsolidated material, while the rivers of semiarid regions cut down into fresh and well cemented rocks. The area of land over which the effect of subaerial denudation approaches that of marine denudation in the production of gravelly waste may be

assumed as equivalent to the area of land over which the annual rainfall is between 10 and 25 inches. While the two are not strictly coincident, this area of rainfall includes the arctic regions, many of the high plateaus, part of the lofty mountains, and in general the regions of semiarid climate.

The area of land possessing a rainfall between 10 and 25 inches is given by Murray as 17,115,350 square miles, 30.7 per cent of the land surface of the globe.[14] It is thought that under the harsh climatic conditions of these regions denudation proceeds at a higher rate than under warmer and wetter climates. Accordingly, a conservative statement appears to be that one-third of the land surface over which mechanical erosion dominates supplies at least one-third of the waste due to fluviatile denudation. As the high mountain tracts, though small in area, are subject to most rapid disintegrative weathering, it is more probable that one-half of the fluviatile waste compares in its gravel content with that derived from marine denudation. Applying these ratios to the total amounts of marine and fluviatile erosion as determined in an earlier section, and remembering also that an overwhelming amount of the fluviatile sediment which is carried to the sea is in the form of mud or sand, it is seen that the gravels supplied by fluviatile erosion are some tens of times greater in quantity than the gravels produced by the erosive action of the sea. The present great dominance in the production of gravel on the lands is related to the existence of broad areas with continental climates and rapid denudation of recently elevated regions. These relations are altered, however, in periods of prolonged crustal quiet marked by wide epicontinental seas, dismembered lands, and world-wide temperate climatic conditions. At such times, and especially when a rising sealevel has rejuvenated marine erosion without stimulating the work of rivers, the quantity of gravel supplied to the sea may have equaled or exceeded that supplied by subaerial denudation.

Part II. Marine Conglomerates

Waves as agents of erosion and transportation

Review of the work of other investigators.—Coastal charts indicate that gravel or shingle is characteristically a beach formation, giving place to sand in moderate depths of water. Exceptions, however, are not uncommon. Along much of the coastline, sand and not gravel may constitute

[14] John Murray: On the total annual rainfall on the land of the globe and the relation of rainfall to the annual discharge of rivers. Scottish Geog. Mag., vol. 3, 1887, p. 74 and plate.

the beach, while off great river mouths mud is the dominant shallow-water deposit. On the other hand, a chart of the English Channel shows gravel in places out to the middle of the channel and at depths up to 70 fathoms. Off the coast of southern California gravel is recorded at depths ranging up to 300 fathoms.

The questions arise, therefore, as to what is the usual effect of waves and currents upon gravel, what is the extent and depth of deposits which may be made through their agency, and why does gravel occur in places at such great distances from land and in such great depths of water? These are problems needing discussion in order to throw light upon the conglomerates of the geologic past, the more so since recent expert testimony before the British Royal Commission on Coast Erosion, as well as a review of British geological literature upon this subject, shows much diversity of opinion.

Murray noted that when ballast foreign to the east coast of England was dumped in 10 to 20 fathoms of water, the shore after storms was strewn with these pebbles, which could only have been brought there by the action of the waves at the depths stated,[15] and Joshua Wilson observed the same phenomenon off the coast of Sunderland. Hunt shows that there is good evidence that on the northwestern shores of Lyme Bay the oblique wave and current action causes the shingle to travel toward the head of the bay, while the sand travels in the opposite direction.[16] He also notes that shells which live in 5 to 6 fathoms are frequently cast up during storms on the shores of Torbay, and in one case a matured valve of *Thracia convexa* was found some 3,000 yards from the only place where he knew of it alive in that locality.[17] During heavy onshore storms, however, beaches are sometimes stripped of their shingle, which is carried out to deeper water and brought back by the more moderate waves of offshore winds or even by the unaided operation of a moderate swell.[18] Finally, in the more powerful storms, although the shingle may be removed, the heavier blocks may be cast landward.

In the minutes of evidence taken in 1906 before the British Royal Commission on Coast Erosion, Clement Reid stated that the shingle was derived from the cliffs, to a certain extent from the foreshore, and in some places was washed up from the sea. For our purposes, the latter two sources may be ignored. The undertow of exceptional storms, however, drags the sand and shingle out to sea, leaving the foreshore tem-

[15] Proc. British Inst. Civ. Eng., vol. 12.

[16] A. R. Hunt: Sci. Proc. Roy. Dublin Soc., vol. 4, 1884, p. 282.

[17] Proc. Roy. Soc. London, vol. 34, 1882-1883, p. 8.

[18] Vaughan Cornish: On sea-beaches and sand banks. Geog. Jour., vol. 11, 1898, p. 537.

porarily bare of beach material. What is left is piled higher up on the beach to the length of the highest waves. The ordinary travel of the shingle is along the shore, but there are exceptional places where it may be moved in 25 fathoms of water.[19]

Whitaker testified that it is mainly fine material which is taken permanently out to sea, not stones.[20] An offshore wind, however, causes the sand from the sea to come in and pile on the beach. This action took place in Portness Bay, Isle of Lewis, from a depth of about 6 fathoms of water.[21] The long maintenance of shingle on a beach without loss to the deep water is proved by the "Hall Sands" immediately north of Start Point, Devonshire. Worth states that the shingle does not work around Start Point in either direction. It consists of flint, quartz, felsites, and a very little admixture of local rocks. A great part of the material was derived from Dartmoor and was brought down by the river Dart when the land stood 100 feet higher than at present. A knowledge of the near-by material in the bottom of the English Channel shows that it could not supply the material, especially as sand lies on the seaward side of the beach. Four fathoms is the limit set by Worth for this locality, and from beyond this depth no beach material is derived. These gravels, undoubtedly undergoing some abrasion, have consequently been kept on that beach since the present level of the sea was attained, some thousands of years ago.[22]

At Dungeness, near the eastern end of the English Channel, there is a blunt cape projecting seaward, and here occurs one of the most remarkable shingles on the English coast. Its base measures approximately 6 miles and from the base to the apex is 3 miles. Its growth since 1782 has been at the rate of 2.61 yards per year. The shingle bank at the point is very steep, lying at an angle of 2 to 1 and sloping down to deep water; at 50 yards from the shore the bottom is mud. The surface of the shingle is from 4 to 6 feet above high water and its thickness is estimated at 22 feet.[23]

Palmer holds that the shingle added to Dungeness Bank travels from the west in water up to perhaps 10 fathoms deep, because Rye Beach, immediately to the west, is of sand. The strong tidal currents along this bottom therefore appear to him to be the dominant agency of transport.[24] In the opinion of others, as, for instance, Clement Reid, the tidal currents

[19] Pp. 102, 103, 105, 110, 113.
[20] Ibid., p. 115.
[21] William Shield: Ibid., p. 172.
[22] R. H. Worth: Ibid., pp. 145-147.
[23] W. H. Wheeler: The seacoast, 1902, pp. 198-200.
[24] Royal Commission on Coast Erosion, pp. 199, 200.

are especially effective in cooperation with the oscillations due to wave action. He notes that on the east coast of England, from Flamborough Head to the Thames, this submarine scour due to a combination of waves and tidal currents is particularly strong close to the coast, while the chief tidal current is often confined to a definite channel between the coast and sand banks outside. During an exceptional northwest gale and a spring tide the whole foreshore bared at low tide was seen to be plowed into deep channels parallel to the cliffs. The action extended out to 15 fathoms, and from this depth heavy slabs of ironstone were thrown on to the shore. A few months afterward all was again shallow sea with a gravelly and sandy bottom.[25]

For present purposes the most important conclusion to be drawn from the facts recited in regard to the effects of waves on the beach and offshore material is that fragments above a certain size tend to be worked shoreward, whereas those below a given size are worked seaward until in a position of unstable equilibrium, oscillating shoreward at certain times, seaward at others. Wave action, therefore, tends to establish and maintain a regular gradation in coarseness from the shore, corresponding to the different portions of the profile of equilibrium of the subaqueous shore terrace.

This statement is supported by certain theoretical considerations on the nature of wave motion. It has long been known that a swell in passing into shoal water is gradually converted by its friction on the bottom into a shoreward wave of translation, and the particles no longer return to their points of starting. Emery, in discussing the subject of the effect of waves upon the shoreward movement of sand and shingle, cites as a test of his theory the fact that bathers when standing upright a short distance from the shore are lifted by the surface wave, and at the same time the landward movement of the ground wave is felt by the legs.[26] According to Fenneman, divers feel the passing of the waves of translation as a sudden landward jerk between intervals of quiet. The undertow, on the other hand, has a steady outward flow except as interrupted by these sudden reverses.

The laws of energy give to these concentrated movements a much greater efficiency than to the same amount of motion more evenly distributed in time.[27] The result is that the heavier material is moved only during the sharp landward impulses, while the finer, lifted by the reverse

[25] Ibid., Appendix no. xi, p. 164.

[26] Emery: Le mouvement des ondes, p. 51.

[27] N. M. Fenneman: Development of the profile of equilibrium of the subaqueous shore terrace. Jour. Geology, vol. 10, 1902, p. 23.

movement and kept almost constantly in suspension, is gradually borne seaward by the undertow which must accompany all waves of translation. The depth of water in which gravels are disturbed, and consequently transported by wave motion, is seldom beyond 10 fathoms, but where tidal currents cooperate with long ocean swells they may be set in motion at depths of 30 or even 40 fathoms.. Hunt further notes that the waves of the English Channel during storms disturb gravels to these depths, the shells of bivalves being occasionally injured at 40 fathoms,[28] while lobster pots are filled with sand and shingle during heavy swells in 30 fathoms.[29] He also notes that the occurrence of unworn shingle at various points westward of Scilly (in depths of more than 50 fathoms of water), the unworn state of chalk flints trawled 15 or 20 miles off the Start and Eddystone, and the character of the fauna of the Channel bed disprove the possibility of such motion at greater depths.

It may be said in conclusion that on a normal bottom profile gravel is no sooner carried seaward than it is sent back toward the shore, an oscillatory movement with respect to the source which has no counterpart in fluviatile transportation. Gravel is thus worn to smaller sizes and gradually tends to be moved seaward, oscillating about new points of equilibrium and taking its part in the wear of the bottom. The depths and the distances to which it may be moved are seen to be narrowly limited. Its natural fate is to be worn to mud, in which state the particles float in suspension, to settle finally far from the shore and at a depth where they are undisturbed by waves. This final comminution is, however, often not attained, owing to the ungraded condition of the bottom and shiftings in the level of the sea.

The wave-formed subaqueous profile of equilibrium.—Where either erosion or deposition has continued long enough for the coastal floor to attain maturity of outline, a certain profile will have become established which will tend to be maintained so long as the shoreline retains its character. This profile, as Fenneman has shown,[30] is a double curve, concave upward near the shore, convex upward farther out, where the outward-flowing currents lose their strength, and again concave upward in deeper water. The steepness of this profile and the degree to which equilibrium is attained are factors in the distance to which gravel may be transported under a permanent water body and the slope on which it may be laid down. Where the initial profile is very flat, the effect of submarine erosion is to cut out the bottom on the seaward side and to throw up a bar

[28] A. R. Hunt: On the formation of ripple-mark. Proc. Roy. Soc., vol. 34, 1882, p. 13.
[29] A. R. Hunt: Sci. Proc. Roy. Dublin Soc., vol. 4, 1884, pp. 285-286.
[30] See also J. Barrell: Factors in movements of the strand-line. Amer. Jour. Sci. (4), vol. 40, 1915, pp. 4-9.

or succession of bars where the waves partially break.[31] Beyond each bar they recover their form and advance with a shorter wave length, finally breaking again in water so shallow as to throw up a beach and shut off the rest of the submerged area as lagoons. Such material as can be kept in suspension is gradually worked seaward, coming to rest in deeper and quieter water. Thus, in time, an approximation to a graded profile is attained by a movement of material both landward and seaward.

Instances of this action on a still ungraded profile are furnished by the coasts of New Jersey, Delaware, and Maryland, the submerged bars or counterscarps being thrown up in depths of from 5 to 10 fathoms (see figure 1, page 307). The bars, being built by waves of translation, tend to be formed of the coarser material thrown shoreward, and constitute a barrier against the seaward wash of gravel from the landward side. If, however, a broad and shallow sea be postulated, whose whole bottom is subject to wave scour, the relations would seem to be different. The waves would then be normal oscillation waves, becoming waves of translation only when shallowing near the shore. Their action on a flat bottom is discussed by Fenneman, who shows that the effect of the waves of oscillation is to drive back the bottom material in the direction from which the waves come. As he says, this is roughly analogous to the wheels of a locomotive, which, in "flying the track," brush the sand on the rails backward. When, however, the wind is blowing at the same time in the direction of wave movement, the effect is to increase the forward motion of the crests and to decrease their backward motion under the troughs. A moderate effect of the wind is probably sufficient to overcome the usual excess tendency to backward movement on the bottom due to the oscillation. The result will be a movement of bottom material forward. This may be neutralized, however, by a resulting undertow.[32] Permanent currents may, of course, still further modify the action.

Neglecting for the present the current effects and applying these principles of wave action to a postulated shallow sea, it is seen that far from shore the drift of bottom material moved with most difficulty will be in the direction of the strongest winds. Nearer the shore, however, the offshore winds are ineffective in generating powerful waves, and consequently the onshore winds will have an advantage in moving the heavy material and tend to drive it shoreward. Within the zone of shallowing water, both offshore and onshore winds drive the material shoreward. While the offshore winds blow toward deeper water, the waves are more nearly of the oscillation type, and in consequence the back scour of the

[31] Lewis M. Haupt: Ann. Rept. State Geologist New Jersey, 1908, p. 88.
[32] Op. cit., pp. 13, 14.

waves moving seaward tends to drive the bottom material shoreward. This deduction seems to be checked by the phenomenon cited regarding the shoreward driving of sand from a depth of 6 fathoms by offshore winds in Portness Bay, Isle of Lewis. The inshore winds, on the contrary, give rise in shallowing water to waves of translation, which, as seen, tend to carry the coarser material toward the shore.

It is thus seen that even in a sea where no part is below wave base, and consequently where material can not be removed to deepen the profile of equilibrium, wave action can not be assumed to act indefinitely in spreading the coarser material over the bottom. On the contrary, wave action, by working most powerfully in the open sea, would tend there to deepen its bottom, the material kept in suspension being carried out by currents, while the coarser material is driven shoreward. By this means a normal profile of equilibrium would finally be attained, permitting the wave systems to be generated and perpetuated with less expenditure of energy.

The case of an initially oversteep subaqueous profile is illustrated by much of the California coast. Sea-cliffs from one to several hundred feet in height are frequent. Their bases rise from tide water, and where the nature of the rock is suitable an abundant shingle beach skirts their base. The United States Coast and Geodetic Survey charts show, however, that gravel as a noticeable bottom material is practically confined within a depth of 20 to 30 fathoms, and this is usually within 2 miles of the shore. The patches of gravel which are reported from greater depths are apparently as abundant at from 50 to 100 fathoms as in shallower water, and have clearly no relation to present wave action. It may be said, therefore, that where a subaqueous profile is initially oversteep, there is no marked sweeping of gravel beyond a depth of 30 fathoms, even when facing an open ocean, and hence such deposits closely fringe the shore. The cases where the slopes are so steep that gravels would slide down by gravity, forming a subaqueous talus, would be, of course, exceptional and temporary conditions, even of a young shoreline.

The profile of equilibrum appears to have been approximately attained off such coasts as the south shore of Long Island, south of Cape Hatteras, and off the coast of Maine (see figure 1, A). The detailed form of the profile becomes adjusted, so that most of the energy of the waves is concentrated at that place where most needed for landward cutting—the surf line. A shelf is cut inland, the boulders and gravel quarried from the subaerial face of the sea-cliff serve as abrasives, and are kept in the mill until small enough to be swept farther out by the undertow. On the seaward side of the upper shelf is a gentler slope, but one steeper

than in the case of the sand bottom, the chief work here being to grind down the rock-floor by means of the cobbles rolled back and forth over it. If the profile be imagined flatter, it is seen that so much energy would be absorbed farther offshore that that remaining at the surf line would not suffice to handle the cobbles; consequently, the inshore erosion would lag until the waves by their erosive power had attained a greater freedom in the deeper water and could expend more of their energy inshore. The result is that gravel may be handled at a somewhat greater depth, but not so far from shore as on a more sandy bottom. On incoherent gravelly material, such as the fluviatile deposits of piedmont coastal plains, the profile of equilibrium would be intermediate, an abundance of gravel requiring a fairly short and steep slope in order that the waves may possess the power to handle it. The shape of the profile for a given material will depend theoretically somewhat on the height and speed of the waves. A powerful ocean swell is as competent to handle gravel as a weak wave system is to handle sand. The first would consequently give a flatter profile to a gravel bottom than the latter and permit the transporting of gravel to a greater distance and depth than in the presence of a weaker wave system. Thus the magnitude of the ultimate profile depends upon the depth of the wave base.

In summation, the profile of equilibrium is a curve variable, both in form and in magnitude, according to the character of the shore and the power of the waves. Its form is further complicated by slow elevation or subsidence and frequently by the effect of lateral currents.

What may be called the normal profile occurs where a gravelly shore and a sandy bottom are exposed to the ocean. Sections off the south shore of Long Island, off Chesil Bank facing the English Channel, and off the Holderness coast of Yorkshire have the same general character. The south shore of Long Island consists of sandy and gravelly, southerly sloping, glacial outwash and is subsiding at a rate of 1.5 to 2.0 feet per century. The flatness of the slope of the land results in sand reefs and lagoons. The south coast of England is approximately at rest and the remarkable Chesil Bank has held the shore stationary for some thousands of years. The Holderness coast, on the contrary, is being eroded at a maximum rate with a stationary water level; the cliffs, which consist of glacial drift, of sand, gravel, and boulder clay, having been eroded back 2 miles since the times of the Romans. The cliffs yield 30 per cent of stones and pebbles, which are kept on the beach, while about two-thirds of the material is fine enough to be worked out to sea.

These three sections have approximately the same depth of water at 10 miles from shore, but within this distance the depths are variable. Furthermore, it is probable that considerable variation could be found along the same coast, so that the individual profiles must not be regarded as possessing exact value. A tabulation and an average of the three curves shows that the Long Island profile is approximately the average.

Subaqueous Profiles (Depth in Fathoms)

Miles from shore	1	2	3	5	10	15	20
South shore Long Island	7	11	13.5	15	19	23	25
Chesil Bank	10	13.5	15	16.5	19	22.5	26
Holderness coast	6	7	8	9	16	22	26
Average of three	7.7	10.5	12.1	13.5	18	21.8	25.7

The average shallow-water profile is distinctly concave upward out to a distance of 3 miles and a depth of 12 fathoms. This gives an average grade of 24 feet per mile, but the curve sinks 20 feet below this average. Beyond this, from 3 to 20 miles, the profile is practically a straight line, with a grade of 48 feet per mile. The storm waves are competent to stir fine gravel off these coasts to a depth of as much as 25 fathoms, but since the gravel tends to be kept near the shore and the sand is deposited farther out, the characteristic offshore shallow-water bottom deposit is sand.

The section through Chandeleur Island, off the Mississippi delta, shows a profile of the same character, but of somewhat less than half the depth, a weaker wave system working here against the alluvial deposits of the Mississippi.

The profiles off the New Jersey, Maryland, and Norfolk coasts show shallow bottoms on which the waves drag, throwing up submarine banks which are further accentuated by the channeling of lateral currents. Such results are obtained through the subsidence of flat coasts. The shore erosion is weakened until the bottom can be scoured out, permitting the waves to spend their energy at the beach-line. Opposite effects occur where headlands project into deeper water, especially where current scour removes the eroded material, as seen in the profile through Saint Albans Head, on the English Channel. Here there is a sea-cliff 100 feet in height which rises inland to 500 feet, and a depth of 20 fathoms occurs 2 miles from shore. This depth is then nearly constant for 10 miles, and a gravel bottom extends to a depth of 30 fathoms and more than 20 miles from land. The gravel, however, has not come from Saint Albans Head, since strong lateral tidal currents are sweeping shore gravels eastward.

MARINE CURRENTS AS AGENTS OF GRAVEL TRANSPORTATION

General statement.—The normal undertow from wave action gives rise in places to concentrated lateral and offshore currents; the semidiurnal tidal waves, when restricted by a shallowing bottom, and especially when passing between converging coasts, give rise to powerful waves of translation. Furthermore, the ocean currents, when impinging against the continents or submarine plateaus, also scour the bottom. The distances to which currents of these several orders may sweep gravel should be examined in order to obtain criteria as to the limits to which in the geologic past such currents may have spread marine conglomerates.

Currents due to wave action.—Lateral currents due to oblique wave action work gravel along the shore, but do not tend to take it out to deep water. The pebbles are rolled up and down the beach and in each upthrust are also moved obliquely, making a zigzag path. Under these conditions, the gravel undergoes an excessive amount of wear for the final distance attained. In lakes and tideless bays there are no effective lateral currents; hence the lateral shifting tends to bank the gravel into the heads of bays and to throw spit bars across reentrants, thereby straightening the shoreline. Where shore currents work from two directions, blunt promontories, such as Dungeness, may be built outward. Their progression can not, however, be indefinite because the gravel is supplied by erosion of the shores, and after stable conditions are attained the recession of the cliffs will also involve a recession of the gravel cape. The superficial nature of the deposit is seen in the case of Dungeness. Here, in the presence of powerful waves and currents, the thickness of the gravel is but 22 feet.

The filling of bays will be found in the thicker gravels lying in hollows of the old surface of unconformity. Such gravels will tail out from the wave-cut ridges, and in the centers of the hollows may possibly rest on finer and variable beds beneath, which represent estuarine or lagoon deposits. Gravel promontories in cross-section will be seen as beds of conglomerate some tens of feet in thickness tailing off to seaward from the old shoreline and lying completely above the surface of unconformity. By being built out into deeper water and with the help of lateral drift, such conglomerates may exceptionally and locally acquire considerable thickness.

The currents produced by wave action may be manifested as a powerful offshore undertow rather than an alongshore drift. Fenneman has noted, for example, that on Lake Michigan, wave base, where revealed by a sharp angle at the edge of a marginal terrace, is 60 or 70 feet below

the surface; yet around much of its margin a sand-covered or gravel-covered bottom, concave upward, extends outward to several times this depth with little or no evidence of change of slope at wave base.[33] Such effects are also to be expected in bays and lakes, for the highly curved and converging shores permit the wind to drive the surface water into these cul-de-sacs, whence it can escape only through powerful undertow. The structural effect of offshore undertow is therefore supplemental in a way to the alongshore drift, tending to fill in the bottoms of indentations, whereas alongshore drift tends to fill them at water level. Beyond the line, where the undertow is restricted by the shore and bottom curves, the mechanical principle of least work requires that the current should expand in cross-section, slacken in velocity, and move slowest on the bottom, rather than continue to scour a channel into which it is no longer held. As seen in geological section, such undertow gravels, like those originating from lateral drift, would also fill in the hollows between prominences of the underlying erosion surface, but probably on a broader scale and with less relation to the bottom than the gravels of the alongshore drift. The variations in thickness of the basal conglomerate would in general be apparently of the same order of magnitude as the topographic relief of the surface of unconformity, and this is less than the original relief, as pointed out by Fenneman,[34] owing to the planing down of the headlands during marine invasion.

Action of tidal currents.—Tidal currents exert more power than wave action upon the sea-bottoms. On the shores the tide also exerts a strong influence on erosion and the movement of gravel, indirectly by permitting the waves to attack the shore and directly by producing waves of translation on the shallow bottom. The direction of movement of bottom and even of shore gravels is held by certain engineers (W. H. Wheeler and L. M. Haupt, for example) to be more largely due to tidal waves than wind waves, though in regard to their control of shore action distinct differences of opinion are held. The tides, however, move the whole body of sea-water, and where any marked shallowing occurs strong bottom currents will be generated, even at depths wholly below the reach of wind waves. Thus, at the outer portion of the continental platform of the English Channel a pronounced rippling of the bottom occurs and muddy water is brought to the surface when the flood tide from the open ocean passes over banks which lie at a depth of 60 fathoms.

[33] N. M. Fenneman: Development of the profile of equilibrium of the subaqueous shore terrace. Jour. Geology, vol. 10, 1902, p. 31.

[34] N. M. Fenneman: Effect of cliff erosion on form of contact surfaces. Bull Geol. Soc. America, vol. 16, 1905, pp. 205-214.

In narrowing channels, such as the English Channel, a large part of the water may attain velocities of several miles per hour. The flood tide, however, gives rise to greater velocities than the ebb tide, and this difference becomes more pronounced with strong tidal effects. Consequently, gravel moved by the tides tends to be swept shoreward rather than seaward. Kinahan states that, with few exceptions, the tidal currents on the coast of Ireland show that they have little or no drifting power when the tide is on the ebb, even when confined in narrow channels.[35] In general, therefore, the tide tends to move bottom material toward the land and into narrowing channels.

The flood tide, following the general laws of stream action, has a greater velocity and a higher surface in the center of the channel than on the margins. The tidal wavelets tend, therefore, to flow in at right angles to the shore, although a lateral effect is, of course, usually present in the general direction of the tidal movement; consequently, the gravel at the shoreline is kept against the shore, although traveling in the direction of the flood tide. Gravel which lies at the bottom of the channel, however, tends to be moved directly along the channel.

Of most importance are the results to be seen in the case of projecting headlands. Here the tide develops an accentuated current and tends to sweep the offshore gravels away from the headlands and across the bottoms of the intervening bays. It can not, however, move them effectively into deeper water. Dungeness is a most striking example of this action, where the gravel travels eastward across the bottom of Rye Bay[36] from the cliffs to the west, and may receive considerable additions from older gravels on the bottom of the channel, because only a portion of the pebbles are of the black flint derived from the western chalk cliffs. The strength of the action is evident, in that 3 miles of land have been added to Dungeness since the eighth century.

The effectiveness of tidal action is largely due to the cooperation of wind waves moving in the direction of the flood tide, for these give rise to a rapid oscillation of the water particles, which on the forward movement is added to that of the steady tidal flow. In addition, the forward movement is accompanied by a lifting one, tending to lift up the bottom, and this is particularly effective on stones to which seaweeds are attached. Observations in the English Channel show that such currents are effective in stirring gravel to a depth of 30 fathoms.

In conclusion, tidal currents affect gravel at greater depths and farther

[35] G. H. Kinahan: The drifting power of tidal currents *versus* that of wind-waves. Proc. Roy. Irish Acad., 2d ser., vol. 2, Science, 1875, p. 444.

[36] Palmer: British Royal Commission on Coast Erosion, vol. 1, pt. 2, p. 199.

from shore than does the undertow; but, whereas undertow tends to spread the gravel beyond the point where the waves have power to bring it back to the shore, the tidal currents, cooperating with the waves, move the gravel landward into some of the most remarkable accumulations at the beach-line.

EXCEPTIONAL LOCATIONS OF MARINE GRAVELS

The preceding discussion has tended to show that marine gravels are not carried beyond depths of 20 or 30 fathoms, nor horizontally to distances of more than 10 or, perhaps, in a few extreme cases, 15 miles from shore; yet observation shows the occurrence of gravel up to 180 miles from land, as off southwest Ireland, and in depths ranging to nearly 300 fathoms, as off the coast of southern California.

It would seem that such occurrences are to be explained in several ways without resort to present wave or current action. Excluding such readily recognized special cases as gravel carried by floating ice, or moving down submerged cliffs due to gravity, it is found that deep-water gravels are ordinarily to be accounted for as of ancient origin and accumulated at former lower levels of the sea. As is well known, the submerged river channels off the continental margins indicate that during the Pliocene and Pleistocene many of the continental shelves were greatly emerged. The strand-line probably migrated more than once during Pleistocene time to the edge of the continental shelves and back again to near its present position. Over certain localities gravel deposits would remain where now nothing but sand or mud is carried by the water. Provided that wave or current action is sufficiently strong to prevent the sand or mud from being deposited on the bottom, but not strong enough to stir gravel, the deposits of the latter would remain permanently bared. Drifting sand would slowly grind down the surface of such gravels to a size where they could be removed and a slow marine erosion would occur. If, however, only mud in suspension is carried by the water to such places, it would seem that such gravels might remain unaffected for even geological periods. Where gravels are found at great depth or distance from the land, but still within the limits of geologically recent shorelines, the previous analysis renders such an explanation the most probable. An excellent example occurs in the admirable paper on the valley of the English Channel, presented by Austen in 1849.[37]. His map giving the relation between the depth and bottom deposits shows that the Channel slopes from 25 fathoms near its eastern

[37] R. A. C. Austen: Quart. Jour. Geol. Soc., London, 1850, vol. 6, pp. 69-97.

end to 100 fathoms at its western one, but at a number of places across the western portion, barriers, such as Jones Bank and the Little Sole, rise to within 40 to 60 fathoms of the surface. Beyond the zones of coarse material that is more or less related to the present coastline is a broad area of the finest quality of muddy sea-bed, whose upper surface is so soft and incoherent that the sounding lead sinks some distance into it. Beyond this area in turn rise the outer banks to within 60 fathoms of the surface, at which depth the moving power of the sea is limited to fine sand; yet their sides, especially the outer or western sides, are covered with coarse materials. Austen directs attention to the fact that the intermediate zone of soft bottom precludes the supposition that coarse materials can have traveled over the mud zones between them and the shore.

"Furthermore, on the sides of the Little Sole Bank and more particularly on its western slopes, large, perfect, though decayed, shells again occur, and, what is more remarkable, *Patella vulgata*, *Turbo littoreus*, etcetera. Taking the two phenomena together, the occurrence of littoral shells and of marginal shingle, we may safely infer that we have at this place the indication of a coastline of no very distant geological period, buried under a great depth of water and removed to a great distance from the nearest present coastline."

An inspection of Austen's map shows many areas of gravel in from 60 to 80 fathoms of water. Where such are separated from the shores by much finer material, the same explanation is offered by Austen. The conclusion, therefore, is that in a region of bottom scour many portions may not be receiving sediments, and that the fragmental beds of such areas may be the exposed portions of ancient shore deposits laid down during a transgression of the sea.

CONCLUSION ON THE DISTRIBUTION OF MARINE GRAVELS

From the preceding discussion it is seen that on open coasts with fixed shorelines marine gravels commonly range from about 1 fathom above high-water level to 4 or 5 fathoms below. They are kept against the coast and seldom extend more than from 1 to 3 miles from shore. They are characteristic of the concave shoreward portion of the subaqueous profile.

The thicker deposits arise in connection with curving shores, especially on young ones, where the deposits of gravel may either fill in bays or build out as spits and promontories.

Exceptionally concentrated undertow from shore reentrants may sweep out gravel to depths of 20 or 30 fathoms, and storms cooperating with tides may sweep gravel across bottoms at depths of 20 or 30 fathoms

and up to 10 miles from land. Marine gravels of fixed shorelines, therefore, though customarily deposited within 3 fathoms of water and within 1 mile from land, may, under exceptional circumstances, extend to ten times these limits.

Distinctions of geological application between local accumulations of unusual thickness of marine gravels on the one hand and similar fluviatile ones on the other may be drawn as follows: The thick marine accumulations have traveled farthest and with distance have become subjected to gradually weakening forces of transportation. Therefore their grain will ordinarily be finer where the deposit is thinner.[38] Fluviatile accumulations of unusual local thickness are, however, valley-bottom deposits of fluviatile fans. The material is normally coarser where the deposit is thinner.

Finally, the thick marine deposits of gravels are exceptional and subject to more rapid change in bedding planes and in coarseness than is the case in the similar fluviatile accumulations.

RELATION OF GRAVEL DEPOSITS TO RISING BASELEVEL

Progressive marine conglomerates (*basal conglomerates*).—Gravels distributed by wave action probably rarely if ever extend 10 miles beyond the shore, and, as the amount of tilting which may take place within this distance while gravel is being deposited is negligible, it is only necessary here to consider the cases of a rising or falling sealevel uncomplicated by tilting of the bottom. With stationary sealevel, marine planation ultimately destroys all coarse materials. With constantly rising sealevel, marine planation will also operate, but at constantly higher levels as the shoreline advances up a slope. It is under such conditions that gravel deposits may be permanently preserved. Where the gravel is derived by marine planation, a limit to the average thickness of the deposit is given by the fact that the gravel comprises but a fraction of the total volume of material eroded. However, as the gravel and sand are partly deposited together, the thickness of the gravelly portion will be somewhat greater than if a clean separation existed. As gravel is not produced below the surf-line and as sea-cliffs do not average over 100 to 200 feet high, it is clear that the average thickness of marine gravels, even if wholly preserved, is less than 100 feet and ordinarily considerably less. This may be taken as a limiting figure, but it remains to examine the conditions under which marine

[38] For an extended treatment of the laws affecting the size of marine gravels, see Vaughan Cornish: On sea-beaches and sand banks. Geog. Jour., Roy. Geog. Soc., vol. 11, 1898, p. 542.

gravels would be most largely protected from continued abrasion to their final complete destruction. Several cases may be considered.

[In the following discussion, as in the accompanying diagrams, it is tacitly assumed that the rock bottom cut by a rising and advancing sea will parallel the slope of the land. Since this is obviously not a necessary relationship, it may be well to point out here why such an assumption is made.

[Of the two independent factors which make for the encroachment of the sea on the land, that of wave-cutting tends to produce a horizontal rock-floor; that of a rising sealevel tends to make the land surface itself the floor of the advancing sea. The slope of the rock bottom can not in any case, therefore, be steeper than that of the land, though it may be flatter. However, as Barrell has just pointed out, the flatter slope would

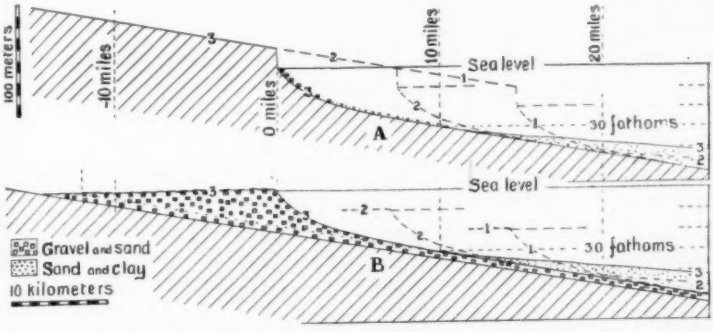

FIGURE 1.—*Deposition of Gravels in Case the Slope followed by the advancing Shoreline is equal to the average Slope of the Sea-bottom at the gravel Limit*

A shows the result in case the gravels are derived by marine planation, B where coarse materials are contributed by shore drift or rivers.

lead to the ultimate destruction of all coarse materials. In seeking to find the maximum thickness to which marine conglomerates may attain, he therefore correctly assumes the condition most conducive to the formation of thick gravel deposits.]

First, *the slope followed by the advancing shoreline is equal to the average slope of the bottom at the limit of gravel deposit,* as shown in figure 1. For approximately graded shores, this slope at a distance of 10 miles from land varies from 5 to 10 feet per mile, and under conditions of a constant ratio between land subsidence and marine planation the cliff heights will remain constant and the slope of the land toward the sea will be the same as that followed by the rising shoreline. As the

portion of the profile on the shoreward side of the gravel limit is steeper than the slope at the limit, the result will be as shown in figure 1, A, a complete planing away of all gravels but a preserval of sands and muds. This is the case where the sea works directly against the land, but if the shoreline is such that there is lateral drift and local accumulation of gravel, the basal portion of this may be permanently preserved, as shown in figure 1, B. At any one stand of the sea the deposit of gravel is limited to 30 fathoms and usually less, but foundation gravels at greater depth may have been accumulated at an earlier and slightly lower sea-level. The thickness of the deposit will depend upon the horizontal distance to which the gravel is built out from the shore and the slope of the rock bottom. The sea, in moving gradually inland at the assumed grade of 5 to 10 feet per mile, will plane 50 to 130 feet off the top of the profile. Consequently, only those portions of the gravel deposit which at the beach-line lie at a greater depth than this will be permanently preserved. An inspection of figure 1, B, will show that in general the gravel beach will have to be built out from land to a distance approximately equal to that at which gravel is distributed under water before a basal portion will be preserved.

Second, *the slope followed by the advancing shoreline is equal to the average slope of the bottom from the beach to the gravel limit* (see figure 2). Here the slope averages about 18 feet per mile, gravel being agitated in extreme cases to a depth of about 30 fathoms at a distance of about 10 miles from land. As shown by the figure, the depth of gravel permanently deposited in front of the cliff face is equal to the depth of the concavity of the profile below the average grade. At a number of localities along the Atlantic shore where equilibrium had been approximately attained, this depth, as determined from the coast charts, amounts to from 30 to 50 feet. Along shores with weaker wave action, the magnitude of the profile is less and the depth of the concavity decreases in nearly a similar ratio. Along those parts of the shore where gravel is stored by lateral drift, figure 2, B, shows that the depth permanently preserved is equal to the depth at the beach-line, but that the upper part of such beach gravels is removed by planation and replaced by finer gravel deposited on the outer half of the curve. With a slope to the rock bottom of 18 feet per mile, the gravel beach would thus have to be built at 5½ miles on this line from the land to attain a depth of 100 feet. This would most commonly occur on the axial lines of estuaries; but, as the head of an estuary of this length would usually be silted by stream or tidal action, the gravels would not reach this maximum thickness, but would rest on finer materials below.

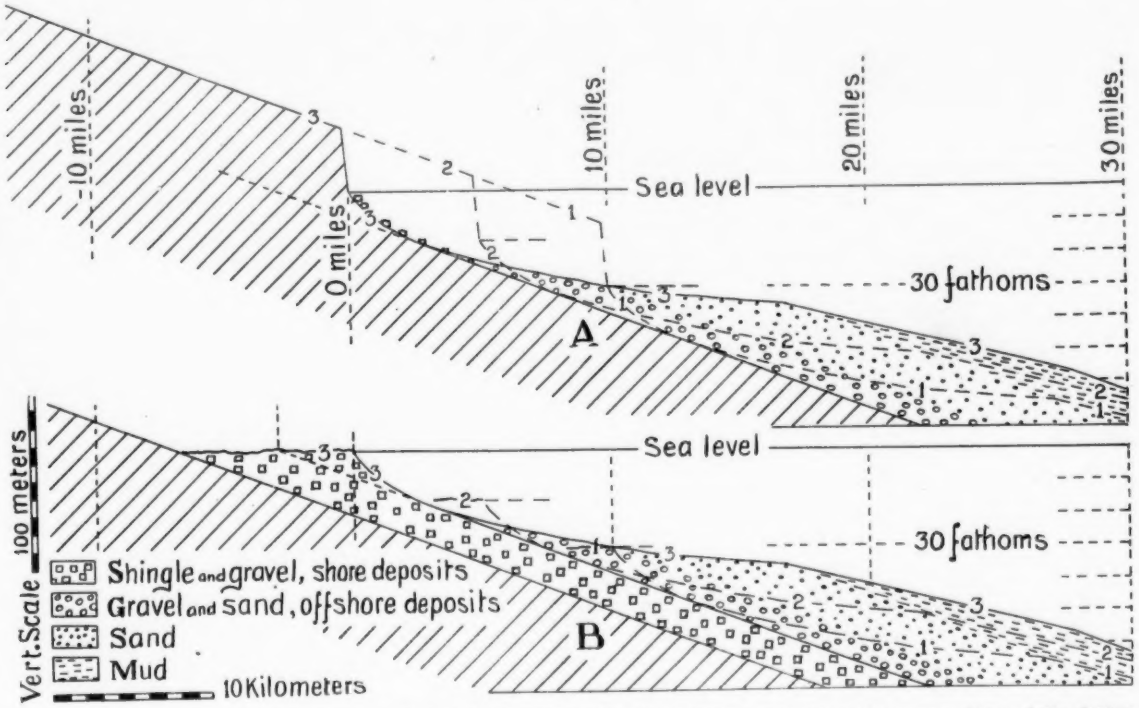

FIGURE 2.—*Deposition of Gravels in Case the Slope followed by the advancing Shoreline is equal to the average Slope of the Bottom from the Beach to the gravel Limit*

In A the coarse material is all derived from marine planation, and in B there is a contribution of gravels by shore drift or rivers.

Third, *the slope defined by the advancing shoreline is greater than the average slope of the bottom from the beach to the gravel limit* (see figure 3). As the slope of the land and of the rising strand-line becomes steeper, the profile of the offshore bottom becomes steeper and the 30-fathom line representing the extreme gravel limit is found nearer shore. The depth to which gravel may accumulate may then be expressed in terms of the slope of the land and the distance of the gravel limit from shore, for it will be 30 fathoms less than the depth of the rock-floor at the gravel limit. [To illustrate: If the slope of the land (and of the

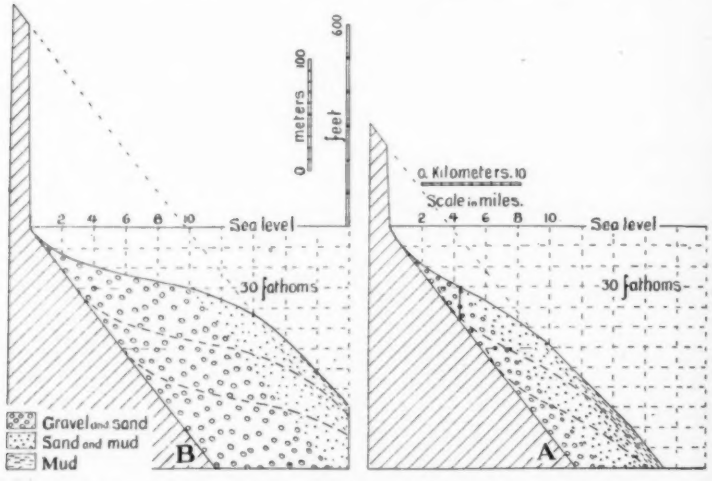

FIGURE 3.—*Deposition of Gravels in Case the Slope followed by the rising Shoreline is steeper than the average Slope of the Bottom from the Beach to the gravel Limit*

In A the gravel is all derived from the shoreline, and as the volume of sediment is not great the gravel limit depth of 30 fathoms is near shore. Contribution of coarse material by shore drift produces the results shown in B, where the greater volume of accumulating sediments builds a broader platform and the gravel limit is farther offshore.

rock bottom) be 70 feet per mile and the gravel limit 4 miles offshore, the thickness of the gravel will be 100 feet. If the gravel limit be 2 miles offshore and the slope 140 feet per mile, the thickness would likewise be 100 feet, while a slope of 180 feet would give a depth of gravel of 200 feet.] It is evident, therefore, that with a steeply rising sea-bottom against a land of considerable relief, the depth of gravel is not limited by the conditions of gravel deposition, but by the height of the cliff and its ability during erosion to furnish a certain amount of gravel.

On such steep shores, as illustrated by the charts of the California coast, lateral wave action tends to sweep the excess of gravel away from the promontories and accumulate it in the reentrants of the coast, where the conditions will approximate to those shown in figure 3, B.

Fourth, *the seaward slope of the land and the slope of the rising strand-line are irregular* (see figure 4). In marine transgression it must be assumed that the sealevel does not rise at a uniform rate, and that the land has to some degree an irregular relief. These assumptions will result in a shifting of gravel-making conditions. The surface of

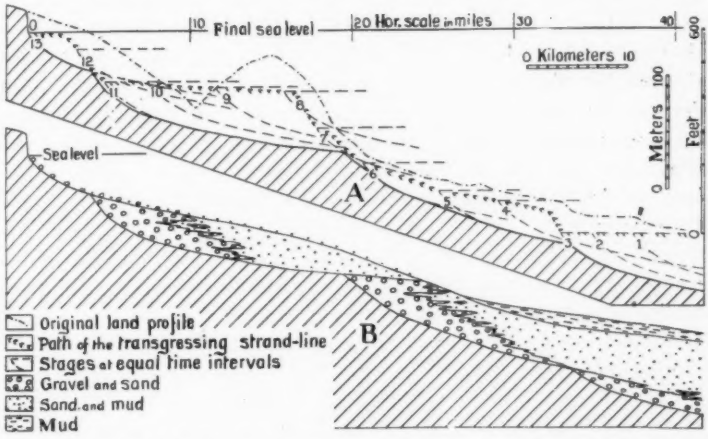

FIGURE 4.—*Deposition of Gravels resulting from irregular Transgression occasioned by an irregular Land Surface and an irregular rising of Sealevel*

The profile developed is shown by A, and the distribution of sediments by B. In A the position of the shoreline at successive equal time intervals is indicated by the numerals 1 to 13. An inspection of the diagrams show that similar effects may be produced by inequalities of surface or irregularities in the rise of sealevel.

marine planation will be irregular in both directions, gravels will not cover the higher portions of the rock surface, but will be restricted to the slopes and hollows. Accordingly, the mantle of conglomerate will be uniform in extent and thickness in proportion to the smoothness of the bottom it rests upon.

In conclusion, it has been seen that the most favorable conditions for the accumulation of thick marine conglomerates are those where the sea is transgressing (= rising) against a land of some relief. The conglomerates made in this way are rather readily recognized, because they are basal conglomerates developed upon an erosion surface of an older

rock formation. They rapidly grade above into finer-grained, offshore, marine deposits. An important case to be considered, however, is where the sea is transgressing a gravelly coastal formation, especially a fluviatile deposit. Such formations, if extensive, have seaward slopes of less than 18 feet per mile and may have slopes of not more than 5 or 10 feet per mile. From the preceding discussion it is seen that the sea, though cutting deeply inland, would in the flatter cases leave no conglomerates save where beach cusps might be built out from the land or where occasional rapid rises in the ocean level carried the shoreward gravels below the reach of wave action before they had been worn out in the mill of the surf. Where the gravelly deltas are more limited in area, they may be steeper in slope, ranging from 18 to 100 feet per mile. Where the sea rises against the land on similar grades, the surface of the fluviatile deposits may be transformed into marine conglomerates to depths depending upon the grade. On account of lack of knowledge of the marine profiles in each case, no exact thickness of the marine conglomerate can be given, but it may be stated as of approximately the same thickness as the grade per mile of the fluviatile deposit, thus giving a relation easily remembered. For instance, with a grade of 20 feet per mile, the advancing sea, under varying conditions of profile, may lay down an average thickness of 10 or 30 feet of gravel. Therefore 20 feet may be used as a mean estimate of the depth of marine gravel on gravelly land surface sloping 20 feet per mile.

Consequently, if such a widespread formation as the Pottsville conglomerate, implying fairly low surface grades, were laid down by rivers adjacent to an advancing and retreating sea, it is seen that the conglomerates where thick are typically fluviatile beds, and even where thin will in general represent fluviatile deposition rather than deposition by an *advancing* sea.

Regressive marine conglomerates.—(See figure 5.) Following an advance of the sea, a retreat takes place, owing either to a progressive elevation of the sea-bottom or to stationary conditions with a continued supply of detritus, giving rise to a seaward overlapping of coarser beds, as discussed by Rutot, by Wilson, and by Grabau.[39] Such an arrangement of beds is aptly termed by Grabau *regressive overlap*, and where the beds are marine and of a pebbly nature they may be named *regressive marine conglomerates* (figure 5, A).

Upon a lowering of the water level, the wave action is increased on

[39] A. W. Grabau: Types of sedimentary overlap. Bull. Geol. Soc. America, vol. 17, 1906, pp. 613-615.

the offshore bottom and scouring takes place. A part of this material, especially the coarser, will be thrown up on the landward side as beach deposits, a part will be worked seaward to deeper water. In this process sorting will occur, but the coarsest particles of the new beach materials can not be coarser than the materials from which they were derived. Rivers, however, will trench the newly elevated coastal plain, and tend to supply the surf with pebbles derived either from their upper portions or from the newly elevated marine gravels. In this way not infrequently

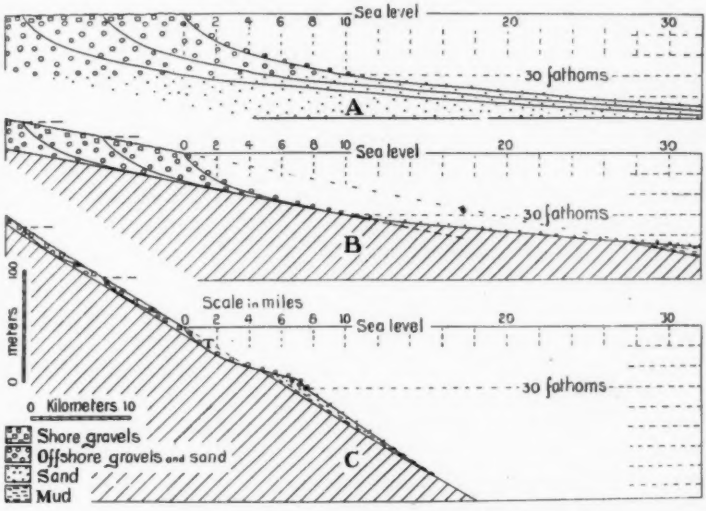

FIGURE 5.—*Formation of regressive marine Conglomerates*

A shows the effects of stationary sealevel, the regression being due to outbuilding by alluvial deposits from the land. Here the ultimate thickness of the conglomerate is that of the depth of the gravel limit.

B and C illustrate the effect of regression due to lowering of the sealevel. In B the rate of lowering of the sea is such that the slope defined by the receding shoreline parallels that of the sea-bottom at the gravel limit. The thickness of the conglomerate is here much less than the depth of the gravel limit.

In C the lowering of the sealevel is more rapid, the slope defined by the receding shoreline being steeper than the bottom slope at the gravel line. Its effect is to still farther reduce the thickness of the retreatal conglomerate. In this case the withdrawal is assumed to be irregular, with the result that terraces of the gravels faced by low sea-cliffs are left by the retreating sea.

a gravelly deposit coarser than the material below may mark the retreat of the sea and constitute the upper limit of a marine formation.

It was seen that in the advance of the sea over a flat land the tendency was to eliminate gravels through their being kept against the land until

worn to the size of sand. During the retreat of the sea, however, the tendency to keep the coarser materials near the shore will cause them to be abandoned and preserved from further wear. It is seen, therefore, that during a marine retreat it is more difficult for the sea to supply itself with gravelly material, since it no longer has a rock bottom to work upon; on the other hand, if such material is supplied, as it usually is, by rivers, the chances are more favorable for a deposit of gravel. The depth of the marine gravel thus laid down will depend on the depth of wave scour, as shown in figure 5, A. Although under exceptional circumstances gravels may be borne seaward to depths of 30 fathoms, the scour which is here indicated seldom goes deeper than 10 to 15 fathoms. The marked upper phase of the retreatal conglomerate will consequently be less than a hundred feet in thickness, although streaks of finer gravel carried outward by the undertow may be found interbedded in sand to depths of somewhat over 100 feet, where the nature of the coast made such outward-flowing bottom currents unusually strong.

Since a lowering of the sealevel is usually irregular, the deposition of the retreatal conglomerate will be subject to variations. When a rapid drop in the sealevel occurs, prominent beaches will be left behind, fronting terraces of marine gravels whose slope was given them by the subaqueous profile. An excellent example is to be found at Quaco, New Brunswick. On the other hand, when the level becomes stationary, the sea will begin to plane inland, remove its gravels in doing so, and cut a sea-cliff. When, however, the sea once more retreats, a veneer of gravel will be left to mark the subaqueous portion of the profile. Such gravels are necessarily of a surficial nature, but their porous nature preserves them from erosion and their quartzose composition prevents chemical decay. They are, therefore, capable of persisting for a long time, but as a rule are destined to ultimate destruction through the headward erosion of streams or the scouring of a readvancing sea. The most favorable case for the preservation of regressive conglomerates is that where the sea, either stationary in level or slowly rising, is being displaced by advancing gravelly deltas, the river action in this case burying and preserving instead of destroying the abandoned gravels of the sea.

The characteristics of such surficial gravel deposits are a gentle seaward slope interrupted by steplike descents or gravelly bars extending at right angles to the slope of the surface or parallel to the sea. If buried beneath overlying formations, the usual relations visible to the geologist will be those of a transition conglomeratic bed between finer-grained marine strata below and coarser but more poorly sorted thick fluviatile

conglomeratic beds above. Texturally the lower transition should be the sharper, biologically the upper.

Examples of the surficial class of retreatal conglomerates are found mantling many regions recently emerged from the sea. One of the most striking is the accumulation of water-worn pebbles and boulders of an average thickness of perhaps 30 feet which mantle the plains of Patagonia everywhere except in some of the basalt-covered areas. They overlie the marine Cape Fairweather beds of late Pliocene age, and, save for the interruptions due to abandoned sea-cliffs, may be traced from the Andes into the shingle of the present beach-line. These facts, along with the occurrence of recent shells and skeletons of cetaceans far inland and partly buried in the shingle, led Hatcher to the correct conclusion that this formation represents the continuous shingle beach left by the retreat of the sea during the Pleistocene and Recent uplift of Patagonia. Where exposed in sections, it is seen to consist throughout of a heterogeneous mass of water-worn stones, with but a slight admixture of sand and clay. The materials are generally unstratified and appear as a bed of coarse, loose conglomerate unconformably overlying the older sedimentary rocks beneath. It occurs alike on the pampas and in the valleys, as well as over the slopes of the latter.[40]

The Atlantic coast of the United States also furnishes examples in the several subdivisions of Pliocene and Pleistocene gravels, as described in recent reports of the New Jersey and Maryland Geological Surveys. These deposits are each less than 100 feet in thickness, usually much less, and may carry gravel lenses throughout. The coarser material occurs mostly near the base and to a lesser extent near the top. The gravel is also coarser near rivers, and it is not improbable that some of it is fluviatile, since certain of the peat and clay beds are known to be of terrestrial origin. Low sea-cliffs, however, clearly terminate the interfluvial portions.

No attempt has as yet been made to indicate more ancient examples. As a rule, their sharp demarcation may be found impossible, but their presence is probable wherever marine strata are conformably overlain by thick masses of conglomerate. Such relations are especially common, for example, in the Coal Measures of eastern North America and western Europe and in the Miocene deposits flanking the great Alpine-Himalayan mountain system. The great importance of the distinction here made is that marine fossils found in fine-grained intercalated beds or

[40] J. B. Hatcher: Princeton Patagonia Expeditions, vol. I, Narrative and Geography, 1903, pp. 221-224.

in the basal portion of an overlying conglomerate carry no implication of a marine origin for the thick upward extensions of the conglomeratic formations. Such alternations between sea and land conditions have been frequently determined through the presence of both marine and terrestrial fossils. In the formations cited, owing to the abundance of land plants in both the Carboniferous and the Miocene, the structural relations strongly supplement such evidence, and even where there is an absence of all fossils in the conglomerates their origin may be proved by the inherent physical structure.

Part III. Conglomerates of the Lands

Relations of Velocity to Transportation in Rivers

The earliest experimental determinations of the stream velocity necessary to move different-sized matter were made in 1786 by Dubuat,[41] whose results are the primary source of most subsequent statements on the subject. He experimented with different kinds of material, colored red, in water flowing through a trough 60 feet long, and carefully noted the various bottom velocities. His results are tabulated as follows:

Dubuat's Experiments

	Velocity at bottom per second.		
	Material stable.	Critical velocity.	
	French inches.*	French inches.	Meters.
Brown pottery clay.....	.....	3	.08
Fine sand from this clay.....	.....	6	.16
Coarse yellow sand.....	7	8	.22
Gravel coarse as aniseed.....	3	4	.11
Gravel coarse as peas.....	6	7	.19
Gravel coarse as beans.....	8	12	.32
Gravel one inch and more....	17.5	24	.65
Angular flints, egg size.....	24	36	.98

Although the results given in this table are of great value, there is danger in applying them directly to nature, since widely different results

[41] Dubuat: Principes d'hydraulique, vol. ii, p. 95.

* One French inch equals 1.06 English inch. In the first column are given the highest *measured* velocities at which the materials remained motionless. At the slightly higher velocities of the second column movement was initiated.

may be obtained in observations on rivers, as is shown by the following determinations by Suchier,[42] cited by Penck:[43]

Velocities in Meters per Second at River Bottom

	Meters
A. River bed smoothed with fine clay:	
No spontaneous movement of pebbles visible at	0.70
After stirring:	
Gravel size of beans	0.90
Gravel size of hazelnuts	0.92
Gravel size of walnuts	1.06
Gravel size of pigeon's eggs	1.12
B. River bed washed bare:	
Smallest pebbles move freely at	1.18
Pea and hazelnut sizes move freely at	1.25
Perceptible noise of pebble movement at	1.30
Walnut sizes move freely at	1.48
Pebbles of 250 grams weight after stirring	1.48
Stones of 1,000 grams weight roll at	1.59
C. General movement of gravel:	
Restricted to pigeon's egg sizes at	1.62
Restricted to hen's egg sizes at	1.72
Pebbles of 1,500 grams weight move occasionally with the above.	
Pebbles of 2,500 grams weight in movement at	1.80
All pebbles in movement at	2.06

Suchier's results show that under the conditions on the bed of the Rhine the velocities of bottom current are all distinctly higher than those obtained by Dubuat. Furthermore, the relations between the bottom velocity and the mean velocity of the stream are highly variable, according to the character of the stream. For shallow ones, the value may be about one-half of the mean velocity, for deep rivers it may be 90 per cent of the maximum top velocity. The variation in stream velocity in a vertical line follows the law of a parabola whose axis is parallel to the surface but somewhat below, the position of the axis and size of the parabola varying with the stream. This parabolic curve does not, however, fully account for the great difference between the results quoted, and the explanation is probably to be sought along lines suggested by Sorby.[44] From certain theoretical considerations, he concludes that the actual velocity necessary to move sand is about a sixth of the observed mean velocity of the shallow stream on which he experimented and about

[42] Suchier: Die Bewegung der Geschiebe des Oberrhein. Deutsche Bauzeitung, 1883, no. 56, p. 331.

[43] A. Penck: Morphologie der Erdoberfläche, vol. I, 1894, p. 283.

[44] H. C. Sorby: On the application of quantitative methods to the study of the structure and history of rocks. Quart. Jour. Geol. Soc. London, vol. 64, 1908, p. 179.

a third of that given by Dubuat. At the very bottom, therefore, the law of the parabola fails, owing to the cohesion of the water to the sand. Dubuat's measurements of currents rolled along an artificial bottom were also made closer to the bottom than are most measurements. In addition, it is to be noted that bottom material, after being stirred up and once in motion, is moved by a lower velocity of current than that necessary to set it in motion. This difference is greater for sand and fine gravel than for coarse gravel.

The velocities of streams are customarily given as mean velocities or surface velocities. Therefore the values given by Suchier as necessary to move various materials are lower than the usually cited velocities of a stream just competent to do this work. That values of river currents necessary to move gravel higher than those given by Dubuat prevail in nature is shown by comparatively sluggish rivers, which leave their gravel burden upstream and carry nothing coarser than fine sand. When the great variations in river actions are noted in different parts of its channel, in different parts of its course, and under different topographic and climatic conditions, it is seen that the transporting power of rivers must be studied by actual examples, and that these must govern all general conclusions.

EXAMPLES OF GRAVEL DISTRIBUTION BY RIVERS

Comparatively few observations have been made as to the distances to which present rivers are carrying gravel along their beds. More frequent information is given regarding the dry terrace gravels, but these seldom indicate the nature of the river action. As a rule, the maximum velocities and depths of water, the proportion of fine and coarse waste, and the distance traveled are not considered. Generalizations based on actual phenomena are, therefore, difficult to draw, but some controlling observations may be cited.

Medlicott and Blanford note that pebbles are scarce in the Indo-Gangetic alluvium at distances greater than 20 to 30 miles from the hills bordering the plain, while the difference in height between the top and bottom of the slope nowhere exceeds 1,000 feet.[45] Clay and sand are the characteristic materials of the alluvium. The slope of the plain of the Ganges from Delhi to Allahabad is 409 feet in 360 miles, or more than one foot per mile. Comparisons with the grades of other large rivers show that the narrow limits to which the gravel is carried are

[45] H. B. Medlicott and W. T. Blanford: A manual of the geology of India, pt. 1, 1879, pp. 397, 403.

doubtless due to overloading of the Indus and Ganges with fine waste rather than to an inability of large rivers, if underloaded, to move gravel on this grade.

The eastern slopes of the Andes also furnish significant evidence in relation to the transportation of gravel. Here precipitous mountain walls rise abruptly from the alluvial basins, which are as flat and boundless to the eye, when viewed from the mountain slopes, as the wastes of the open ocean. In this region the belt of rains extends about 5 degrees south of the equator, but the high Andes cause rain to fall at all seasons down to about latitude 17. Farther south the rainfall is seasonal, occurring in the summer, but south of latitude 28 the belt of westerly winds prevails and the climate of the eastern slopes becomes arid.

In the belt of heavy equatorial rains the mountain slopes are saturated with water, and the torrential rivers, flowing through deep gorges, finally pour onto the plain, where the grade rapidly flattens to less than a foot per mile. Church says that the Içа, one of the main branches of the Amazon, was ascended by Crevaux in a steamer drawing 6 feet of water. Not a single rapid was encountered on the way to Cuemby, 800 miles from its mouth and only 200 miles from the Pacific Ocean. Its elevation above sea at its mouth is 245 feet, and at Cuemby is 985 feet, giving a fall of 740 feet in 800 miles. There was not a stone to be seen up to the base of the Andes; the river banks were of argillaceous earth and the bottom of fine sand.[46]

In central Bolivia, between latitudes 15 and 16 south, Isaiah Bowman states that the plains at the base of the mountains are about a thousand feet above the level of the sea. The base of the mountains is here a fault-scarp from 1,000 to 4,000 feet in height, and the uplift has been so recent that even in this well watered country the rivers issuing from the mountains are still ungraded.[47] The Chaparé, known as the Juntas above its junction with the San Antonio at the foot of the mountains, flows north into the Mamoré. The latter is the main river, flowing through the broad alluvial Mojos basin somewhat over 500 feet above sealevel. The following detailed observations on the distribution of gravels are in part from the article cited, but largely from unpublished field-notes:

[46] George Earl Church: South America, an outline of its physical geography. Geog. Jour., vol. 17, 1901, p. 368.

[47] Isaiah Bowman: Physiography of the central Andes. Amer. Jour. Sci., 4th ser., vol. 28, 1909, pp. 374-375, 395.

The Chaparé River

Grade of River Plain

From	Elevation in feet	Distances in miles.	Grade, feet per mile.	To	Elevation in feet.	Remarks.
A	12,000	8	325	B	9,400	
B	9,400	7	271	C	7,500	
C	7,500	30	150	D	3,000	
D	3,000	29	48.3	E	1,600	
E	1,600	15	33.3	F	1,100	Base of mountains.
F	1,100	15	14.7	G	880	Santa Rosa.
G	880	22	4.6	H	780	1.5 miles below last gravel.
H	780	10.5	2.9	I	750	End of journey.

Grade of River

A	12,000	8	325	B	9,400	
B	9,400	7	271	C	7,500	
C	7,500	30	150	D	3,000	
D	3,000	29	48.3	E	1,600	
E	1,600	15	33.3	F	1,100	Base of mountains.
F	1,100	20	11.0	G	880	F-G = Piedmont slope.
G	880	43	2.3	H	780	Meanders pronounced.
H	780	20	1.5	I	750	On central basin.

The river is now actively building up its floodplain, which for some 20 or 30 miles from the mountains lies in a shallow valley a mile or two wide. The valley disappears below and the floodplain merges into the broad alluvial basin. The walls of this valley have gravels deposited when the stream flowed at a somewhat higher level, toward which it is again building. As a result of the present aggradation, the floodplain extends into the mountain gorge from 5 to 10 miles. Down to the locality where corrasion ceases, the river is full of huge boulders. At this point the grade changes rapidly from about 30 to about 15 feet per mile. The river from here to Santa Rosa is a slightly meandering and braided stream, with rapids due to accumulations of small boulders, cobbles, and pebbles. At Santa Rosa, 15 miles from the mountains, the coarser material ranges from 8 to 10 and 12 inches in diameter. From the point where navigation begins, about one-half mile below Santa Rosa, a second character of the stream begins. It now flows on a grade averaging about 5 to 3 feet per mile, and begins to meander to such an extent as to approximately double the distance across the plain. For a few miles the bars are almost wholly of gravel, but 6 miles below Santa Rosa one

can discern pebbles only in patches on the upstream side of the bars. At about 35 miles in a direct line from the mountains and about 60 miles by river, the last gravels were seen on the upstream side of a bar and ranging up to 2 inches in diameter. Beyond this point for nearly 100 miles, to Trinidad, only sand was observed, and the open plain slopes between 2 and 3 feet to the mile, but the grade of the river is between 1 and 2 feet to the mile.

In drawing generalizations it must be borne in mind that each tributary of the same river system will show differences in grade and transporting power. The more powerful streams can move similar material on a flatter slope and hence to a greater distance with the same vertical fall. Consequently, broader studies must check the results derived from a single example. In this illustration of the Chaparé is seen, however, the relation between changing grade and changing character of load. On the other hand, when the width of the piedmont gravels is compared to the width of the whole aggrading basin, some conclusions may also be drawn between the relative volumes of coarse and fine waste.

The gravel deposits on the well watered piedmonts of the Himalayas and the Andes are limited in area and volume compared to the gravel slopes in the dry regions of central Asia. As an extreme example, Colonel McMahon notes that east of the Lake of Seistan gravel extends as a plain from the nearest mountain in Baluchistan to the lake bluffs, a distance of 150 miles, descending in this distance 2,500 feet—an average of 16.6 feet per mile. In such regions the material is coarse and angular near the mountains, but fine-grained and rounded at a distance.

Piedmont slopes of gravel from 10 to 40 miles wide are not uncommon, though belts from 5 to 10 miles wide are the most usual, descending from 1,000 to 2,000 feet or even more. Therefore the narrower piedmonts are built by weaker streams at a grade of from 100 to 300 feet per mile, while the broader ones are due to more powerful stream action on flatter slopes. On the other hand, the broad and comparatively steep slopes of gravel skirting the mountains and lying between them and the silts of the central basin floors are due to the cooperation of two causes—the withering of the streams upon entering the desert valleys and the large proportion of coarse material resulting from the mode of weathering in arid climates.

As an illustration of the action of graded streams flowing from mature mountains in a semiarid climate may be cited the High Plains lying to the east of the Rocky Mountains and consisting of upper Tertiary

clays, sands, and gravels. These deposits constitute the remnants of an alluvial formation with a grassy level surface.

Haworth and Johnson both note that gravel is found throughout the limits of the Tertiary in streamlike courses, though subordinate in quantity to the sand and clay. The deposits extend eastward somewhat over 400 miles from the mountains, the source of their origin.

Regarding this matter, Johnson writes as follows:

"Where there is no erosion of the surface there is no gravel at the surface. The eroded areas of the Plains Tertiary here and there show superficial gravel; the High Plains surfaces do not. They have a hard 'adobe' soil, except where, over comparatively small areas widely separated, it is covered by drifting sand. But well sections, canyon sections, and the shallow beginnings of erosion at the plateau edges occasionally show gravel close to the surface. All sections, artificial and natural, whether near to the mountains or far out, show a no less frequent occurrence of it at one level than another. Nor is there observable any graded variation in the size of the gravel, up or down, in section. There is gradual diminution in size from the mountains outward, but the rate of this diminution seems to be the same at all levels.

"The maximum size of gravel in the High Plains belt is that of cobbles. Material so coarse as this is quite uncommon; yet from northern Kansas to the southern limits of the Staked Plains of Texas the writer has occasionally found beds of cobbles, and no more frequently at one level than another, though seldom, as we have seen, any coarse material actually at the surface, upon the uneroded uplands. Individuals of larger size—boulders—are here and there to be found. As a rule, these are not thoroughly rounded; they are of the nature of erratics, and probably have been transported either by river ice or in uprooted trees, and they may be of the softer rocks, such as sandstone, while invariably the gravel in beds is hard.

"But though boulders and beds of cobbles are rare, in sections of the High Plains, smaller material, which would still be regarded as coarse gravel, is comparatively abundant."[48]

The work of Gilbert, Haworth, and Johnson has proved that these Tertiary beds were laid down by the same rivers which now flow through them. The trenching is ascribed by Johnson to the climatic changes of the Pleistocene, and the rivers are now to some extent filling up their valleys. The Arkansas, for 500 miles from Pueblo to the south boundary of Kansas, has an almost constant slope, with an average of 7 feet per mile.[49] The North and South Platte exhibit very similar characteristics.

Johnson has argued that the grade of the streams which laid down

[48] W. D. Johnson: The High Plains and their utilization. U. S. Geol. Survey, 21st Ann. Rept., 1901, pt. iv, pp. 633-634.

[49] Henry Gannett: Profiles of rivers in the United States. U. S. Geol. Survey Water Supply and Irrigation Paper No. 44, 1901, p. 63.

the Tertiary deposits must have been nearly that of the present rivers. We therefore see that gravel has been moved more than 400 miles down a descent of more than 3,000 feet, giving rise to a conglomeratic formation in which, however, the gravels, though conspicuous, constitute but a minor portion of the whole deposit.

In order that gravel may be conspicuous in an alluvial formation, it must constitute a considerable portion of it or indicate its presence through its water-bearing properties. In a living stream a gravel bottom is readily seen, because it is kept bare by the currents which have brought it into place. Where great variations in the velocity occur, however, such gravels may be more or less blanketed by sand during the low-water stages.

In this connection the careful studies which have been made of the Mississippi are especially valuable. Humphreys and Abbot state that the substratum upon which the river-borne material rests, from the mouth of the Ohio downstream, is a hard, blue or drab colored clay. On this the channel deposits of the river are laid, and consist of immense beds of pure siliceous sand and fine gravel, entirely free from the muddy silt with which the water is charged. The coarser material is found in general wherever the water moves too rapidly to deposit its fine sediment. On the other hand, the material becomes finer as the gulf is approached.[50]

At Red River landing the bottom material was chiefly small gravel and coarse sand. At Carrollton, just above New Orleans, at all stages of the river, it is sand with earthy matter.

An inspection of the charts of the Mississippi River below the mouth of the Ohio confirms these statements and indicates that the gravel has traveled great distances on gentle slopes. From Memphis to Vicksburg the river flows well out in its floodplain and is separated from the bluffs by back swamps, yet gravel is found abundantly at Memphis and at intervals all the way to Vicksburg, occurring in patches up to 1 or 2 miles long and up to half a mile in width.[51]

Gravel is found at depths of from 10 to 100 feet of water and always where the current is strong. The surface gradient of the river decreases from 0.4 foot per mile at Memphis to 0.24 foot per mile at Vicksburg, or a grade of less than 3 inches to the mile. Gravel is recorded to a point below the mouth of the Red River. From the mouth of the Ohio to this place the distance is 450 miles, not including meanders. The largest tributaries of the lower Mississippi are dammed back by the aggradation

[50] A. A. Humphreys and H. L. Abbot: Physics and hydraulics of the Mississippi River, 1861, pp. 98, 149.

[51] See, for example, charts nos. 28, 38, 43.

of the main stream, so that they can not be regarded as feeders of gravel. On the other hand, the bluffs, themselves former river deposits, may furnish a minor contribution, but it seems clear that a graded master river like the Mississippi can carry fine gravel for many hundred miles along its channel at stream gradients of but 3 to 5 inches per mile. The maximum current velocities in this part of the river, as measured by the Mississippi engineers during high-water stages, approach 7 feet per second (= less than 5 miles per hour) at a depth of 5 feet below the surface. The calculated bottom velocities vary from 5 to 15 per cent less than for those of the subsurface. At low-water stages the velocities are from one-half to one-quarter of those of high water. As one foot per second is regarded as a velocity sufficient to sweep along fine gravel, the river is seen to be theoretically competent to do the observed work. Furthermore, Humphreys and Abbot, on the basis of the material in suspension, regard the Mississippi as underloaded,[52] and this is doubtless an important factor in the ability of the river to roll forward the coarser waste which it receives.

Turning to the rivers of the eastern United States and south of the limit of glaciation, those flowing east over the piedmont to the fall line in Pennsylvania, Maryland, and Virginia are seen to possess in general grades of from 2 to 4 feet per mile.[53] South of Virginia, the grades across the coastal plain are less than 1 foot per mile, but over the piedmont they range from 1 foot per mile upward. The larger rivers flowing west from the Appalachians have gradients of less than a foot per mile after leaving the mountains, the Tennessee descending 307 feet in the last 402 miles and the Cumberland 175 feet in 339 miles.

The eastern streams, because they are well graded, in a region of abundant rainfall, and are not overloaded by finer waste, are in general able to carry coarse gravel as far as the fall line, as indicated by the character of their beds and also by the extensive coastal mantle of Lafayette and later gravels. That these materials are mainly of river origin is proved by their increased coarseness near the river mouths and the fact that they extend up the river valleys. These river systems offer a fine field for the study of the relations between grade, depth, velocity, and character of material carried, and one that has as yet not been systematically taken up; but, from such general observations as the writer has been able to make, it may be said that the larger streams can carry fine gravel on a grade of 1 foot to the mile, coarse gravel on a grade

[52] Op. cit., p. 139.
[53] Henry Gannett: Op. cit.

of 2 feet to the mile, and cobblestones on a grade of 3 feet to the mile. The capacity of a river to carry gravel has doubtless been most carefully studied in the case of the Rhine, for the upper part of which Sternberg gives the following data:[54] It enters a down-faulted valley at Basel and flows through it to Mainz. From below Basel to below Mannheim it receives no gravel from tributaries, and hence the power of the river to move gravel can be definitely measured. The river gradient at high water at Basel is about 1 meter per kilometer, and at Mannheim about 1 meter in 10 kilometers. The velocity of the current at high water below Basel is 3.60 meters per second, and near Mannheim it is 2.40 meters.

The following table gives the data regarding the gravel in the bed of the Rhine, as measured in the spring of 1872:

Gravel in Bed of Rhine

	Length of stream course from Hüningen (just below Basel).	Number of pebbles in .027 cubic meter (1 cubic foot).	Weight of largest pebbles.	Remarks.
	Kilometers.		Kilograms.	
A	.7	600	5.9	
B	29.1	1,211	4.7	
C	55.9	1,540	2.9	Average of three measurements.
D	91.4	7,500?	2.2	Number of pebbles appears unreliable.
E	139.8	1,900	1.5	
F	180.3	4,821	1.0	Mean of three measurements.
G*	261.6	5,876	0.1	Mean of six measurements.

For purposes of computation it may be assumed that a cubic foot of these pebbles contains 20 per cent of pore space. Let the specific gravity be taken as 2.6; then calculation shows that with 600 pebbles per .027 cubic meter the average weight of a pebble is 94 grams, or 3.4 ounces. The average diameter, assuming the pebbles to be spherical, is 4.1 centimeters, or 1.6 inches. The table shows that in traveling 180 kilometers from Hüningen, the pebbles were so reduced that it required eight times as many to occupy a cubic foot. Since the volumes of similar solids are proportional to the cube of the diameters, these pebbles were, on the average, reduced to one-half of their initial diameter—that is, from 1.6

[54] H. Sternberg: Untersuchungen über Längen- und Querprofil Geschiebeführende Flusse. Zeits. f. Bauwesen, vol. 25, 1875, pp. 483-506.

* G is at Mannheim, below the mouth of the Neckar.

inches to 0.8 inch. Adjusting this result to the other observations somewhat increases the distance traveled, leading to the conclusion that along the upper Rhine a journey of 200 kilometers is necessary to reduce the average diameter of pebbles from 1.6 inches to 0.8 inch. It is found by plotting the weights of the largest pebbles (see Figure 6) that they fall on a rather smooth curve and apparently conform in this case to a law that they are about sixty-four times the weight of the average pebble—that is, that they are about four times the diameter. This, then, gives the range in heterogeneity of these Rhine river gravels that are moved under conditions very favorable for regular sorting.

RELATIONS BETWEEN DISTANCE AND WEAR OF GRAVEL

From the previous discussion of the relations of rivers to gravel transportation, it was seen that streams from lofty mountains do not carry gravel to great distances, whereas streams flowing at a slighter grade, from moderately elevated uplands, may carry gravel equally far. Therefore, before these examples can be used to explain the geologic past, a further discussion is necessary in order to consider the factors which control this result.

From observations by various investigators cited by Penck, the latter states:[55]

"The transportation of bottom material occurs in general through rolling and but seldom through sliding. The rolling of pebbles is accomplished either in mass or by individual movement. In the first case the whole bottom material of the river is in movement and one hears the striking of stones against each other. The bottom moves as a kind of water-impregnated stream of gravel which, according to the observations of Pestalozzi on the Rhine at Ragaz and the Birsig at Basel, may have a depth of more than three meters. Such transport in mass of large pebbles seems to occur only in mountain streams and indeed only at high water, whereas the finer and more sandy portion is more frequently moved in suspension. The usual mode of transport of the bottom material is intermittent. The water pushes upon the broad side of the pebble, so that it revolves about its long axis and rolls a short distance. Its path, according to J. Schmidt, is sinuous during mean and low-water stages, owing to the spiral movement of the water. During high-water stages the motion is more nearly a straight line. According to Hübbe, the sand advances along the stream bed at the same time in the form of 'waves.' Instead of waves, however, one may better speak of gravel or sand banks, which rarely fail to occur in rivers.

"It appears, however, that the transportation of the individual pebbles is not continuous, but is alternate, in that the pebble once set in movement rolls upon the upstream side of the gravel bank. Once brought over the bank,

[55] A. Penck: Morphologie der Erdoberfläche, vol. 1, 1894, pp. 284-286, 292.

the pebble lies in quiet water like a roof tile, inclined against the direction of the stream. Each bank therefore grows downstream as its material is carried away from the upstream side, and thus the banks journey downstream in a regular manner. On the middle Rhine a bank travels yearly from 200 to 400 meters, and in years of high water three times as far. After seven years a bank occupies the place of the one which at the beginning of that period lay immediately below it. . . .

"According to Sternberg, the wearing down of a pebble is proportional to its weight in water and the distance traveled."

This rule is seemingly the best present expression of knowledge on the subject and agrees fairly well with the observations on the gravels of the upper Rhine, but much experimental verification on stream action is needed before it can be safely used as a general principle. It is a law of frictional resistance that the work of overcoming friction varies directly with the force and distance; but the energy of impact, an important factor in corrasion, varies directly with the weight and with the square of the velocity. At any particular point in a stream the small pebbles tend to travel farther and faster than the large,[56] but the questions to be solved before Sternberg's law can be safely applied are: (1) Does coarse gravel of one point of a stream move with the same velocity when in motion as does fine gravel at a lower point in the same stream? Does the abrasive effect vary directly with the energy of impact, or is a certain initial energy used up in overcoming elastic resistances and not in abrasion?

Assuming for the present that this law may be applied for gravel ranging in size from 40 millimeters (the Basel average) to 2 millimeters (the limit where gravel passes into sand), it was seen that along the upper Rhine an average diameter of 40 millimeters was reduced to 20 millimeters in traveling 200 kilometers. In the second 200 kilometers it would accordingly be reduced to 10 millimeters, in the third unit distance to 5 millimeters, and in the fourth to 2.5 millimeters. As some of the gravel is coarser than the average, this gives about 1,000 kilometers, or 625 miles, as the distance of travel necessary along a graded river course like the upper Rhine to wear gravel the size of hens' eggs down to sand.

Sternberg's observation that the wear on the pebbles during transportation is proportional to their weight is an exponential law and may be mathematically expressed as follows:

[56] See Daubrée, Géologie expérimentale, 1879, pp. 250, 251, footnote on observations on the bed of the Rhine.

W_0 = weight of pebble at initial point;
W_1 = weight of pebble at distance l;

Then $$\frac{W_1}{W_0} = e^{-\lambda l}$$

where λ is a constant and e is the base of Naperian logarithms.

As the weight of the average pebble in the bed of the Rhine falls to one-eighth in traveling 200 kilometers,

$$\lambda = \frac{log\ \overset{8}{e}}{200} = .0104 \text{ and}$$

$$\frac{W_1}{W_0} = e^{-.0104l}$$

In order to find the per cent of wear for the first kilometer traveled, make $l = 1$;

Then $$\frac{W_1}{W_0} = \frac{1.0000}{1.0105}$$

Dropping the last two decimal places as of no significance, this means that at the end of any kilometer a pebble in the bed of the upper Rhine weighs 1 per cent less than before. By means of the same formula, it may be found that half the weight of a pebble is lost in traveling 66.6 kilometers, and that pebbles will be reduced from 40 millimeters to 2 millimeters in diameter in traveling 864 kilometers. Considering the particles which are removed from the pebbles to be entirely below 2 millimeters in size, the volume of the resulting gravel when reduced to 2 millimeters in diameter will be but .000125 of what it was when the diameter of the pebbles was 40 millimeters. They would, therefore, finally constitute but a vanishing fraction of the whole deposit and could not be observed unless continually concentrated by the currents of the river channel.

As the law of the wearing down of gravels along a graded river bed is of considerable importance, the writer has calculated the ratios of weights and diameters which the Rhine gravels show, and also the results according to the exponential law that the wear is proportional to the weight of the pebble and the distance traveled, as follows:

Comparison of actual and theoretic Wear of Gravel in the upper Rhine

	Length of stream course from A.	Ratio of average weights of pebbles.	Ratio of weights of largest pebbles.	Ratio of weights given by exponential equation, 0.5 weight lost in 66.6 kilometers.	Ratio of average diameters of pebbles.	Ratio of diameters of largest pebbles.	Ratio of diameters given by exponential equation, 0.5 weight lost in 66.6 kilometers.
A	0.0	1.000	1.000	1.000	1.000	1.000	1.000
B	28.4	.495	.809	.744	.791	.932	.906
C	55.2	.390	.494	.563	.730	.790	.826
D	90.7	. ?	.383	.389	. ?	.726	.730
E	139.1	.316	.255	.235	.681	.635	.617
F	179.6	.124	.170	.154	.499	.554	.536
G	260.9	.102	.017	.066	.467	.257	.405

Figure 6 gives the results graphically. Even though the observations show the presence of disturbing factors, they fall on both sides of the theoretic curve and indicate its general truth. Except in the observations at the last point, the diameters of the largest pebbles are seen to range remarkably close.

As the gradient of a graded river also follows a logarithmic curve,[57] it therefore follows that both size of gravel and gradient of a single stream are related, under the same general law. This gives valuable information as to the maximum distance to which a stream may carry its gravel, but the simple problem must now be left in order to study certain of the complications which nature introduces.

The rate of wear derived from the study of the gravels of the Rhine has a far better value for geological purposes than those derived from the experimental results of Daubrée and Erdmann. The former carried on his experiments in a revolving cylinder, the latter in an oscillating trough. In neither case is the movement similar to that along the bed of a stream. Daubrée found that rounded granite fragments lost from .004 to .001 of their weight per kilometer traveled.[58] Erdmann found that similar fragments averaging 28.33 grams lost .004 of their weight per kilometer.[59] The highest rate of wear attained by both is only 0.4 of the rate of wear of the Rhine gravel, which presumably is, on the average, as resistant as granite. This is an unexpected result, since the

[57] H. Sternberg: Op. cit.
[58] Daubrée: Op. cit., p. 250.
[59] A. Penck: Op. cit., vol. 1, 1894, p. 293.

opinion has been expressed that the conditions of disordered movement and sudden arrest of motion attending the experiments lead to an excessive rate of wear. If the absolute amount of the abraded material were the same for each kilometer, notwithstanding the diminished size of the pebbles, the latter under a wear of 0.4 per cent per kilometer would be completely destroyed in traveling 250 kilometers; Erdmann gives 278 kilometers. Applying the exponential law, however, it indicates that with this rate, one-half the weight would be lost in 174 kilometers, and

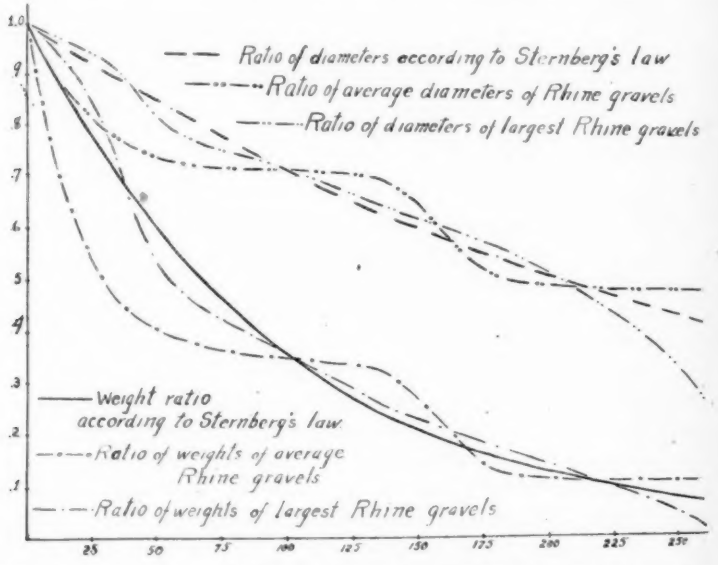

FIGURE 6.—*Curves to show the Rates of Decrease in Diameter and in Weight of Gravels as a Result of Transportation in Rivers*

The distances traveled are plotted as abscissas and the ratios of resultant to original size as ordinates.

This figure was not found with Professor Barrell's manuscript, but was constructed by C. O. Dunbar from the data given by Barrell on page ——.

to reduce pebbles from 40 to 2 millimeters diameter would require a journey of 2,250 kilometers.

It seems, therefore, that some condition must exist in river action which, in spite of the orderly nature of the work, must lead to an excessive wear of gravel during its movement downstream. A chief factor in this wear is doubtless to be found in the large amounts of sand which are swept over the gravel. While the pebbles are at the surface of the

bank and subjected to such wear as is due to their own movement, they are at the same time subject to the wear of all finer material passing over them. In the middle and lower portions of a stream such wear is vastly greatest in quantity. Furthermore, the coarser material only moves at high-water stages, while the sand moves during the entire season of stream-flow.

The tendency of abrasion by sand is to smooth off the upstream side of a boulder. When this is so large as to be turned over only at long intervals by undermining and current action, the result is a faceted subangular boulder analogous in origin to the wind-faceted pebbles of deserts. When the stone is sufficiently reduced in size to be occasionally turned around a vertical axis or turned over, the wear becomes accentuated on the two sides and an oblate spheroidal form results. When so reduced that it begins to move freely downstream at high-water stages, the wear, being now chiefly on its equatorial zone, tends to bring it to a prolate spheroidal form. The structure of the stone, however, exercises a strong influence upon the final form taken. Furthermore, beyond a certain limit, rounding does not readily go; so that what are commonly spoken of as well rounded stones are usually spheroidal rather than spherical in form. Owing to their very slow travel in proportion to their rate of wear, the most conspicuously rounded stones in a river are often the oblate spheroids.

In river stones of massive structure the form is, therefore, of great significance. Those which are not freely moved by the river in high-water stages and whose forms indicate that fact may be defined as stones abnormal to the river course. They may be looked upon as erratics launched into the river from precipitous valley walls or abnormally steepened tributaries; or, in postglacial stages like the present, left by a retreating ice-sheet. Floating river ice or trees are also minor contributors of erratics in the river gravel. Such erratics must pass through characteristic shapes before taking on the forms common to the river. One of the best illustrations of this action is seen in sections of modified drift. These may dovetail into till in such a manner as to indicate a local origin of the modified drift, yet the largest boulders in the latter are more or less water-worn and glacial scratches are removed. The middle-sized boulders are often beautifully rounded to spheroidal forms, more commonly oblate than prolate, and show rounding to greater perfection than smaller material which has traveled much farther. The close restriction of these larger rounded stones to the vicinity of the till indicates the limited degree to which such material travels downstream. The movement appears to be more analogous to the creep of boulders

down a hillside by undermining and downward push than to the normal forward rolling of true river gravel. Excessive variations in the stream action, owing to concentrated rainfall and torrential discharge, are favorable for downstream movement of river erratics in a manner analogous to the influence of strong seasonal changes in promoting the creep of residual boulders down the slopes of the land. Even in such cases, however, as seen at the mouths of mountain gorges, a movement of a few miles downstream appears to be all that is necessary before the boulders are so reduced by wear as to become normal to the river system.

From this discussion it follows that the shape of pebbles and their range in size as they occur in ancient conglomerates form a study of great importance, which may be capable in some cases of detecting disturbances in the river gradient, especially those due to topographic rejuvenation during the progress of vanished physiographic cycles.

This analysis of the normal and abnormal characters of gravel brings the discussion to another factor bearing on their rate of wear. In the headwaters of mountain streams, not only must the stream transport such material as it is able to carry, but, furthermore, none of the material fed in from talus and glacier is initially of the regular forms and sizes which the river tends to produce; there is, therefore, here also an assimilation of waste by the river. Hence the problem arises as to what is the rate of wear of these erratics until they take on the normal shapes, stated in terms of distance carried, and what are the marks of the process of assimilation?

Bonney has studied the action of Alpine rivers upon their bottom material.[60] In the torrential headwaters of the streams descending some hundreds of feet per mile, he notes that the stones which vary in size from boulders downward are generally subangular, even the smaller pebbles not being well rounded. These headwaters are mostly from 3 to 5 miles long and descend from 1,000 to 3,000 feet. The commonest size of stones is from 3 to 6 inches in diameter. Some of them, however, are fairly well rounded, and for such Bonney suggests the possibility of rounding through pothole action.

In the second stage of the Alpine rivers the individual mountain torrents have united, but they are still bounded by mountains and flow rapidly on grades commonly of more than 10 feet per mile. In general, the stones range from about 3 to 6 inches and frequently up to nearly 1 foot, with occasional large boulders. The amount of rounding is

[60] T. G. Bonney: Observations on the rounding of pebbles by Alpine rivers, with a note on their bearing upon the origin of the Bunter conglomerate. Geol. Mag., dec. iii, vol. 5, 1888, p. 60.

variable, but the majority of average-sized stones vary from subangular to moderately rounded, while well rounded pebbles are rare. The materials are gneisses, more or less granitoid, schists, limestones, and grits.

The third and last stage of the Alpine rivers, for present purposes, begins where they issue from the "gates of the hills" and commence their journey through the lowland plains. The grade here falls to a unit of feet per mile. The first case examined was that of the Po at Turin. The river has moved across 35 to 50 miles of plain, while the tributaries have courses in the mountains from 15 to over 30 miles long. The stones exposed near the banks were seen to consist chiefly of Alpine rocks and are commonly 3 to 4 inches in diameter, but some attain to about 8 inches, together, of course, with smaller ones. As a rule, they are not well rounded, but more or less subangular, though the corners and edges are worn off. Similar results were seen in other tributaries between Turin and Milan.

From these facts Bonney draws the following conclusions:

(1) The rapidity with which a pebble takes on a definite form depends, *cæteris paribus,* on the nature of the rock.

(2) Pebbles are rounded with comparative rapidity when the descent is rapid—that is, when they are dashed down rock slopes by a roaring torrent capable of sweeping along blocks the size of boulders.

(3) Pebbles are rounded with comparative slowness when the descent is gentle and the average pace of the river is just about able to push them along its bed.

(4) As indicated by Daubrée's interesting experiments, the process of rounding, *cæteris paribus,* always goes on more rapidly at first.

Bonney's conclusions are given because he observed the facts, while the present writer, treating these facts in connection with a theoretical discussion, would express the conclusions somewhat differently. It is noted that the rounding is not marked in the three earliest divisions of the rivers. In the first stage the commonest size of stones is from 3 to 6 inches in diameter, in the last stage from 3 to 4 inches. The maximum size, however, decreases from boulders, in the first stage, to stones about 8 inches in diameter, in the last. From these facts, in connection with the following discussion, the present writer would conclude:

(1) Aside from pothole action, there is no evidence that the rate of abrasion on rounded stones per *unit distance* is notably higher in the case of mountain streams than in those of the plains. In the Rhine gravels it is 1 per cent per mile, but in mountain streams may be somewhat higher.

(2) The larger stones, those above 6 inches in diameter, when moved by torrential currents, are liable to be shattered by the energy of their own impact against the bottom or against other boulders, and be broken into smaller fragments. In this way the larger stones are subjected to a more rapid reduction in size, but in the process yield an angular gravel instead of the usual silt or slime.

(3) The angular nature of stones fed into the river or produced there by impact leads to an initial higher rate of abrasion, as is seen in Daubrée's experiments.

(4) Boulders, or what we have termed river erratics, are subjected to great wear without much movement downstream.

(5) In the second and third stages of Alpine rivers, the maximum limit of size of the true river cobbles is just about twice the diameter of the average, or the same range as those of the Rhine gravels.

There yet remains to be considered the method of wear of true stream pebbles in the swifter headwaters of the river or at exceptional high-water stages lower down. Then the gravel, instead of moving leisurely through the top layer of pebbles and rolling over those below, is moved bodily as a stream of rock. The relative wear due to the passage of sand over the gravel is diminished, but the wear of the pebbles due to collisions with each other is probably increased. The energy of impact is proportional to the sum of the masses in collision multiplied by the square of the difference of their velocities. Deep in the gravel stream the mass will involve a line of pebbles behind those colliding, provided that this line of pebbles is moving in actual contact, but the differential velocities will be small. On account of the disordered movements of the gravel stream, it seems necessary to rely on experiment rather than theory as to what will be the ultimate result. The experiments of Daubrée and Erdmann involved movements of this nature. The fact that the maximum wear upon granite pebbles per unit distance was practically identical in the two types of experiments gives greater value to the results. When it is noted, however, that the rate of wear was less than half of that of the Rhine gravels, it is apparent that such mass movement of gravels along the bed of a stream does not apparently lead to excessive wear. At high-water stages, however, the Rhine is thought to move its gravels more or less in mass, so that the comparison between the experiments and the Rhine is not as clean cut as would be desirable.[61]

[61] The velocity of the Rhine at high water is stated by Sternberg (op. cit., p. 495) to be as follows: Below Hüningen, 12 feet = 3.6 meters; at Kehl, 10 feet = 3.0 meters; farther downstream, perhaps near Mannheim, 8 feet = 2.4 meters.

In conclusion, therefore, it is seen, from such data as are available, that while the mode of wear differs in the upper and lower portions of a stream and during high- and low-water stages, there is no evidence that the rate of wear and consequent rounding per unit distance of the true river gravels, as distinguished from river erratics, is greater in one part of a river course than in another.

RATE OF WEAR IN DIFFERENT RIVER SYSTEMS

Although one rate of wear may apply to the gravel of a single river, it is evident that it can not be applied without correction to other rivers, which flow on other gradients under different climatic conditions and having other kinds of rocks. Expressed mathematically, the value of λ in the equation $\frac{W_1}{W_0} = e^{-\lambda l}$ (see page 328) is controlled by these physical factors. There appear to be few data to guide a discussion on this topic; but, arguing deductively, it may be said that gentle gradients to the whole system give lower stream velocities with the same volume of water and a greater difference between the mean and bottom velocities. Hence the transportation of silt and sand is favored over that of gravel. The gravel moved will, of course, be finer; but that is a different matter from its rate of wear. The relatively greater difference between the velocities of the sand and gravel in the stream of gentler gradient but equal volume would apparently produce a greater wear on the gravel per unit distance moved. This conclusion should be tested by studies on rivers of the southern Appalachians, since the rivers flowing in different directions from the divide of the Blue Ridge have markedly unlike gradients.

Climatic conditions which favor an equable flow through the year probably favor a low rate of wear on gravel. On the other hand, where sand only is moved throughout the greater part of the year, this condition favors excessive wear of the gravel. In the previous case the volume was regarded as constant and the gradient variable. In this case the gradient is regarded as constant and the volume variable. In variable streams a greater rate of wear might, however, become a smaller one if the run-off becomes so torrential as to move the gravel banks bodily instead of exposing all of the moving gravel to the abrading effect of the passing sand.

Again, where the nature of the rock or the processes of erosion provide a high proportion of silt and sand to the gravel, the latter probably lags upstream and in its slower movement is subjected to a more rapid

wear by the greater volume of sand. Warm and humid climates and lands of low relief are, therefore, probably less favorable for prolonged transportation of gravel than are those of opposite character. The very obvious relation that the rate of wear holds to the hardness of the pebbles must also be considered. Daubrée in his experiments found that rounded fragments of feldspar lost 0.2 per cent of their weight per kilometer traveled. Flint, on the contrary, lost but 0.02 per cent, being ten times more resistant. Where soft and hard are mixed together, the difference in rate of wear is still more accentuated. This is shown by the use of flint cobbles in ball mills for pulverizing cement slag or other products, and the same result is attained on the English shingle beaches where flint cobbles are present. The rapid disappearance of softer material from gravel may likewise be noted in descending a stream from the point whence it was derived, as Walther notes in the case of the Avisio.[62]

The Rhine is a stream of considerable volume, of mean length, and without abnormal seasonal fluctuations. Its ability to move gravel with minimum wear should, therefore, be good, and from its graded middle course the result was deduced that its gravel lost half its diameter in traveling 200 kilometers. In this distance, therefore, differential wear would completely separate the hard from the soft material. Consequently, if in ancient fluviatile deposits occasional pebbles of feldspar and granite or other less resistant materials occur of the maximum size of the quartz, it may be inferred that the distance of transportation has been but a fraction of 200 kilometers. It is the maximum size of pebble and not the relative numbers which leads to this conclusion, since the conditions of erosion may supply the stream with the granite or other débris in finely disintegrated form. The possibility of a nearer source of supply for the softer material or of other transportation would also have to be considered.

Another factor bearing on the rate of wear of gravel is found in the relative rates of movement of the gravel and the sand. Dubuat found that a coarse yellow sand was unstable in a bottom current of 8 inches per second, and a fine sand was deposited at 6 inches per second, while gravel as coarse as aniseed was unstable in a current of 4 inches per second. Gravel as coarse as peas and upward was moved at 7 inches, and that the size of beans at 12 inches.[63] There is thus an exception in Dubuat's table to the rule that the coarser material requires a stronger current to move it. His determination of the greater ease with which

[62] J. Walther: Einleitung in die Geologie, 1894, p. 758.
[63] Dubuat: Principes d'hydraulique, vol. II, 1786, p. 95.

fine gravel is moved than coarse sand has never heretofore been commented on, but his work was done with such great care that his results can not be regarded as mistakes.

Recently Sorby, in a posthumous article,[64] gave the results of experiments made a half century before. He showed that very fine sands when immersed in water act more as a liquid than coarse sands, becoming more mobile and subsiding less quickly than the small diameter of the grains would alone account for. In the coarse sands this tendency disappears and the sand is more compact. On the other hand, the individual grains of the surface layer when at rest do not project as in gravel, and consequently give a current less proportionate surface to act upon. Furthermore, the adherent film of water doubtless to some extent blankets the mass and protects it from the stream current. In this manner Dubuat's results in the case of sand may be explained.

If a fine gravel is associated with a coarse sand, the conditions are favorable for moving the gravel as rapidly as the sand, if not more so. The wear produced on the gravel by the passage of a large volume of sand is thereby eliminated and most favorable conditions occur for the most distant transportation of gravel. The present writer has, however, argued in a previous paper that a climatic change which involves greater flow and transporting power of rivers, especially if the change be a rapid one, will cause the rivers to load themselves with the sand and gravel which may previously have been laid down along their middle courses and sweep this detritus over the delta or deliver it to the sea. The stratigraphic result will be a widely extended sandstone or conglomerate formation intercalated between more argillaceous formations, which because of its significance may be called a climatic sandstone or conglomerate, as distinguished from those of marine and tectonic origins. As the finer material was not laid down in such original piedmont deposits, and as a secondary sorting occurs in the renewed movement downstream, such climatic sandstones and conglomerates will be markedly free from clay and fine sand. Applying these conditions to the results of the experiments by Dubuat and Sorby, it is seen to be in such formations that fine gravel may occur farthest from its place of origin.

RELATIONS OF UNGRADED PROFILES TO GRAVEL TRANSPORTATION

Gilbert, in his classic paper on the Henry Mountains, showed that the movement of coarse waste absorbs more of the stream energy than the movement of fine; that increase of declivity favors transportation in a

[64] H. C. Sorby: On the application of quantitative methods to the study of the structure and history of rocks. Quart. Jour. Geol. Soc. London, vol. 64, 1908, pp. 171-175.

degree that is greater than a simple ratio. If the finer waste available is not sufficient to wholly load the stream, the next grade will be taken, and so on. Since the deepening and concentration of water progresses as it streams, either its *capacity* increases and the load of fine particles is augmented, or, if fine particles are not in sufficient quantity, its *competence* increases and larger ones are lifted.

When the current of a stream gradually diminishes, as in approaching the ocean, the capacity for transportation also diminishes, and as soon as the capacity becomes less than the load, deposition begins, the coarser particles going down first.[65]

In regions which have not been subjected to crustal or climatic changes for long periods of time, the rivers become graded and the waste is moved from the headwaters to the sea. In such a river system, gravel within the competence of the stream will be carried progressively forward and, if not worn out in transit, will ultimately attain the region of deposition; but in long river systems such a completely graded condition is rarely attained, since the gentle gradient is most sensitive to disturbances. Downwarpings in front of the mountains, or climatic changes diminishing the capacity of the streams, cause a local deposition of the gravel rather than of the finer waste, but the stream can still carry the finer waste which may be derived from the wear of the gravel. Consequently, until the gravel becomes covered and protected, it is subjected to excessive wear. If an ungraded condition is pronounced, a rapid deposition of the coarser material takes place without its being subjected to much wear, and if gravel is moved, it is only the finer, which is, therefore, the sooner worn out. This probably accounts for the comparatively limited distance to which the gravels of the eastern Andes are swept toward the Atlantic. If the ungraded condition is incipient and not pronounced, no deposit may take place, but the larger material, moving more slowly and only at times of exceptional floods, is subjected to additional wear by the finer, per unit distance which it travels.

If, on the other hand, the competence of the stream is increased, the river loads up with this coarse material, the ratio to the finer material is increased, its wear per unit distance is decreased, and it will be swept farther downstream than under stable conditions of grade.

Thus it is seen that the size of gravel and the varying limits to which it may be transported constitute the most sensitive of stratigraphic records as to fluctuating river grades. Rejuvenation of stream power through either crustal warping or climatic change may be thus recorded

[65] G. K. Gilbert: Geology of the Henry Mountains, 1877, pp. 106-111.

by abnormally wide and coarse deposits of gravel. But crustal warping is especially liable to affect different rivers in various ways and by breaking up the river grade to produce pockets in which the gravel is deposited. Climatic change, on the other hand, by affecting broad tracts of country, will in a similar manner affect it over the whole course alike. It is, therefore, such climatic changes especially that will be recorded by the wide occurrence of intercalated sandstone and gravel beds. The similar development of the widely spread Millstone Grit of eastern North America and northwestern Europe is a case in point. Here there is confirmatory floral and physical evidence that the deposition of this conglomeratic formation was accompanied by a climatic change of appropriate nature.

MAXIMUM LIMITS FOR GRAVEL TRANSPORTATION

It has now been shown that rivers vary enormously in their capacity to carry gravel. The upper Rhine wears down its gravel at the rate of 1 per cent in weight per kilometer, and Daubrée found for granite gravel rates of wear varying from 0.4 to 0.1 per cent per kilometer. Under favorable conditions for transportation, due to climatic changes, if the wear is assumed to be 0.5 per cent per kilometer, then granite cobbles 4 inches in diameter represent the common size delivered by the streams on escaping from the mountains. Under these conditions the value of λ in the equation $\frac{W_1}{W_0} = e^{-\lambda l}$ becomes .005, and theoretically it would require a distance of 2,350 kilometers to wear down the cobbles to coarse sand 2 millimeters in diameter, or, roughly, about 1,500 miles to completely wear out the gravel. For a wear twice as great—that is, of 1 per cent per mile—a distance of 1,130 kilometers, or, roughly, 700 miles, would be necessary. Even fine gravel would cease to be a conspicuous factor in the volume of the deposit at a considerably shorter distance. The decrease of size in the gravels of the High Plains in distances of 400 miles from the mountains, and again in equal distances along the Mississippi where it flows over a clay bottom, will check these major limits. It is, therefore, clear that in these cases 400 miles of transportation does not produce more than half the wear necessary to reduce cobbles of 100 millimeters to 2 millimeters in diameter. The Lafayette formation, or Orange sand, of the Mississippi Valley, in the vicinity of the river courses is gravelly to the Gulf, near which oil wells have revealed, at a depth of at least 1,500 feet, sands, clays, and gravels of Lafayette type, but of

Quaternary age.[66] These are very probably reworked Lafayette deposits, as pointed out by McGee.[67]

By studying the decrease in mean and maximum size of gravels over stretches in which tributary gravels have not entered, the rate of wear in Lafayette times may be compared with that which prevails at present. If the Lafayette may be a climatic formation, then a lesser rate of wear is to be anticipated. The dissection of the piedmont formations of the High Plains, if contemporaneous with the deposition of the Orange sand, would furnish an adequate source for much of the sand, but probably not for the gravels near the Gulf, since from the Rocky Mountains to New Orleans the distance by way of the Canadian River is 1,700 miles, by way of the Arkansas nearly 1,900 miles; measured along the valleys, however, the distances are about 1,300 miles.

In conclusion, it is seen that under most favorable conditions gravel may be carried 1,000 miles and possibly as far as 1,500, or even 2,000 miles, before becoming completely worn to sand.

CONCLUSION ON RELATION OF RIVERS TO GRAVEL TRANSPORTATION

It has been seen that rivers commonly move gravels down descents of hundreds of feet from their regions of origin and along horizontal distances of tens of miles. These are both figures of a higher order of magnitude than the tens of feet in depth and the unit miles in distance to which shore action is accustomed to transport gravel. Under favorable conditions, moreover, rivers may sweep gravels from far inland mountains to the margin of a continent and down descents of thousands of feet. Consequently, rivers, as agents of gravel distribution, may be a hundred times more effective than the shore activities. The work of the seas is especially that of moving gravel along the shore and thereby keeping it in the zone of erosive activity, while the rivers move their gravel away from the regions of maximum erosion.

Although graded rivers in regions of fair relief are capable of transporting gravel to regions of deposition, it rarely attains the sea. Under stable conditions of land and shallow sea, the rivers build deltas, except where the marine currents are stronger than those of the river. As soon, however, as the river begins to lose its carrying power by spreading widely in time of flood over the lower river plain, and especially when it begins to subdivide into distributaries, its carrying power is reduced.

[66] G. D. Harris: Notes on the Lafayette beds of Louisiana. Science, new ser., vol. 27, 1908, p. 351.

[67] W J McGee: Lafayette deposits in Louisiana. Science, new ser., vol. 27, 1908, p. 472.

Then the coarser waste is the first to be deposited, and builds the landward side of the delta. The sand and clay build the delta outward and contribute to both marine and subaerial formations; but the river gravel, from its deposition farther inland and at a slightly higher level, is peculiarly a continental deposit. To this normal relation there are, however, frequent exceptions. Disturbances of level of the land with respect to the sea in either direction may bring the river gravels and the sea into contact. Land uplift, by abolishing the continental shelf and steepening the lower portion of the river gradient, will cause the river to deliver gravels to the sea. This was apparently the case at the mouth of the Mississippi during the crustal uplift of the early Pleistocene. On the other hand, land subsidence, if rapid, may bring the sea far over the delta to the margin of the upland and the zone of gravel deposits. Powerful tides and waves, working against lands like Great Britain, which are without great rivers, may result in marine planation. Tidal estuaries prevent in great measure all subaerial deposition.

Lastly, where mountains rise abruptly from the sea, as in the Pacific mountains of North and South America, the products of land erosion are in large part swept directly into the sea, the gravels contributing to the shingle of the beaches, the finer material building a narrow submarine terrace. In mountainous regions without deltas, however, subsidence of the land favors the development of terrestrial gravels in the valleys back from the seacoast, and here they remain protected from the erosion of the sea.

In conclusion, it is seen that gravels of either marine or terrestrial origin require stable conditions for their development. They are local and not widely distributed formations. Marine gravels are most restricted, since they are limited to the margin of the sea. River gravels, on the other hand, may occur over all parts of the lands, but do not tend to attain the sea. Finally, in order that gravel may remain as conglomerate formations, either of terrestrial or marine origin, it must be progressively buried below the zone of erosion.

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SIGNIFICANCE OF TACONIC OROGENY[1]

BY CHARLES SCHUCHERT

(Presented by title before the Society December 31, 1924)

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INTRODUCTION

At the 1923 Washington meeting of the Geological Society of America, Prof. Charles H. Behre read a paper entitled "Structures in the slates of northeastern Pennsylvania," of which an abstract was published in the Bulletin of the Society for 1924. The gist of this paper is that the formations about Slatington and Lehigh Gap have twice undergone orogeny, and that "the earlier (Taconic) movement produced slaty cleavage, close folding with great overturns and thrust-faults, and minor faults transverse to the axes of the folds."

Professor Behre wishes to have it understood that he is not the discoverer of the unconformity at Lehigh Gap. In a letter to the writer, he says:

> "Professor B. L. Miller, Dr. Hintze, and, I believe, Doctor Edgar T. Wherry, all saw the unconformity before I did. It is mentioned in some of Grabau's works, and I. C. White calls attention to it in at least one of his earlier papers."

On August 8, 1924, Doctor George H. Ashley wrote me that he and Professor Miller had gone over the Lehigh Gap area with Behre, and were convinced "that there is a distinct unconformity between the Mar-

[1] Manuscript received by the Secretary of the Society January 20, 1925.

tinsburg shale of recognized Ordovician age and the basal part of the Medina, which is generally known as the Oswego sandstone, or, as it has sometimes been called in this State, the Bald Eagle sandstone. The base of the sandstone obviously lies on the truncated edges of the Martinsburg. Furthermore, the conglomerate pebbles of the Medina contain many fragments of the shale, some of which, at least, appear definitely to be sericitized" like the shales of the upper Martinsburg.

"The existence of sericitized pebbles seems strongly to favor the idea of a pre-Medina movement in the shales. . . . In addition to the obvious beveling of the shales at the contact, there is a distinct difference of the dip and strike of the beds. The sandstone above the contact has a dip of 33° north 15° west; the shales below have a dip of 46° north 40° west. If conditions as they appear at Lehigh Gap are as Professor Behre and Professor Miller interpret them for the whole region, it would seem clear and conclusive that the Martinsburg and the Oswego member of the Medina are separated by an orogenic movement of no small importance."

The youngest member of the Martinsburg shale series is, Behre says in his abstract, "of lower Maysville age," while the overlying conglomerates and sandstones he and Miller believe to be the Oswego-Juniata equivalents. However, Schuchert's experience is that the lower 600 feet of the Medina sandstones at Lehigh Gap have no fossils, that the strata appear to be continuous with those above holding *Arthrophycus*, and that, therefore, all appear to be of Tuscarora time. If so, the time break at Lehigh Gap between the Martinsburg and the overlying sandstones is as long as at Otisville, New York. Accordingly, we are no nearer dating the time of the Taconic orogeny than before. On the other hand, if the lower 600 feet can be shown to be of Oswego time, then the orogeny took place during the later part of the Maysville. In that event we will have to give up our 85-years-long conclusion that the Taconic orogeny came at the end of the Ordovician, or, as we would say nowadays, toward the close of the Richmondian.

In response to this information, and assuming that Professor Behre is correct in his correlations, I wrote Doctor Ashley under date of September 20 as follows[3]:

"If your facts are correct, then the Taconic orogeny of eastern New York is continued at least to Lehigh Gap, Pennsylvania. The most interesting point in your letter, however, is the actual dating of the Taconic disturbance. We have been holding for a long time that it came between the Juniata and Tuscarora, but now you say it occurs between the Martinsburg and Bald Eagle. Accordingly, the Silurian begins with the Richmondian, but this decision is based wholly on diastrophism, a physical factor. Decidedly opposed to this conclusion are the faunal facts, the long European usage, and the

statement that the orogeny in Wales came later in Ordovician time. The Richmondian faunas are modified Black River-early Trenton descendants, while the Silurian heralding does not begin until well toward the close of the Richmondian, and especially in the Gamachian."

History of the Taconic Disturbance

The deformation that has come to be known as the Taconic orogeny had its inception in 1838, in the publications of W. W. Mather, and more especially those of H. D. Rogers. It relates to the area between Becraft Mountain, south of Hudson, and Rondout, in southeastern New York. The clarity with which Rogers saw this orogeny is remarkable and his statement about it is worth quoting:[2]

"That great disturbances of the earth marked the period which closed the formation of the [Hudson River] slate and accompanied the production of the overlying conglomerates and sandstones [Medina], is apparent from the coarseness of the ingredients in the latter rocks, the promiscuous manner in which they have been swept together, and especially from the suddenness of the transition between the fine-grained slate, the sediment of very tranquil waters, and the extremely coarse conglomerate directly in contact with it, the whole aspect of which implies that an enormous mass of sand and gravel derived from strata just broken up was suddenly strewed into the waters where the slate was forming. But if evidence still more unexceptionable be required of an upheave of the bed of the ancient ocean at the epoch immediately preceding the formation of these rocks, we have it, strikingly exhibited, at the northeastern end of the formation, where these conglomerates and sandstones occur on the Delaware and Hudson Canal near the end of the Shawangunk Mountain. They are here displayed near Rondout resting *unconformably* and with a gentle inclination upon the steeply uptilted, contorted, and disrupted strata of the immediately subjacent slate."

It was on the basis of these statements by Rogers and the studies made by Sir William Logan and summarized in his *Geology of Canada* that James D. Dana, in the second edition of his *Manual* (1874), says: At the close of "the Cincinnati era" came the "Green Mountain revolution," when the older rocks "were lifted and folded and crystallized and the Green Mountain region made dry land" (page 212). The evidence for this orogeny, he says, is to be found in the maritime provinces of eastern Canada, the New England States, and southeastern New York (page 215). In the fourth edition (1895) we read that at "the close of the Lower Silurian" the "Taconic mountain-making crisis came," and that the upturnings appear "to extend all the way from the Saint Lawrence Valley to New York City" (pages 386, 531). James Hall in 1882 also

[2] Second Ann. Rept. State Geol. Pennsylvania, 1838, p. 37.

gave a good account of the Taconic orogeny in the *Proceedings* of the American Association, pages 66-68.

In 1921 Thomas H. Clark presented "A review of the evidence for the Taconic Revolution,"[3] and after a careful analysis of most of the literature bearing on all the localities mentioned by Dana, he says:

> "The writer has come to the conclusion that the only orogenic movements at the close of the Ordovician of which we have any record were localized in eastern and southeastern New York State, and that beyond this region there is no evidence of the Taconic Revolution. It is suggested that much of the deformation ascribed to the Taconic Revolution [in eastern Canada and the New England States] may have been due to the disturbance which characterized the Devonian in this area."

I have studied Clark's paper carefully, and, as I have also seen considerable of the geology in the area of the Taconic Disturbance as given by Dana, I must say that I think Clark has made a clear case for the restricted import of this orogeny. It is now known definitely to exist between Becraft Mountain near Hudson, New York, and southwestward at least to Port Clinton, on the Schuylkill River, a distance of about 160 miles. How much farther it may eventually be traced in either direction—and it is certain that it will be so traced—it is impossible to say, but the conditions made by the Acadian Disturbance of Devonian time to the northeast in New England and eastern Canada are such that it will be difficult to unravel here.[4]

Diastrophism and Chronology

In the Blue Mountains the conglomerates and sands are not restricted to Juniata-Bald Eagle time. On the contrary, we see more conglomerates and much more sandstone with *Arthrophycus* in the younger Tuscarora and Shawangunk formations. These facts of sedimentation appear to indicate that the Taconic diastrophism began in Trenton time, that there was mountain-making toward the close of Maysville time, and that there was more orogeny, or, at the least, more elevation, at the close of the Richmondian series. If these surmises are correct, then the Taconic disturbance may be said to have been most decided in the Maysville and again renewed toward the close of Richmondian time. It thus

[3] Proc. Boston Soc. Nat. Hist., vol. 36, pp. 135-163.

[4] At the 1924 meeting of the Society, at Ithaca, Doctor F. J. Alcock told the writer that he had last summer discovered in Gaspé an angular unconformity between the Ordovician and Silurian. Furthermore, that the formations beneath the Silurian are more metamorphosed than are those above the unconformity. These observations, therefore, confirm the statements made by Logan in 1863.

simulates the Laramide diastrophism, which came both before and after Fort Union time.

That mountain-making may be much localized, as appears to be the case for the Taconic orogeny, is supported by the evidence of the limited areas of the Arbuckle and Wichita orogeny of Oklahoma. Furthermore, a few years ago Doctor Bruce L. Clark, of the University of California, wrote me that he knew of at least one angular unconformity in the Cenozoic strata of the Coast Ranges that was traceable for only 100 miles.

I therefore conclude that the Taconic orogeny may or may not have the importance of dividing two series of strata into as many systems of rocks, namely, the Ordovician and Silurian.

It has been said by a good stratigrapher that "diastrophism affords the only means of finally attaining a reasonably accurate and systematically constructed classification." Diastrophism here includes all crustal movements; but even so, how are we to know their import geographically and chronologically without the help of fossils? The two sets of facts must be used together, with the further help that paleogeography and the strata can give. In other words, we must use all the evidence available in our delimitations of the various time units, and their separation must be based on the sum of all of our knowledge.

Some of us have held heretofore that the orogenies would easily delimit the periods and eras of geologic time, since it was believed that they occurred wholly in the later parts of these time divisions. Yet we know that the Acadian Disturbance of northeastern North America began in Middle Devonian time and ceased seemingly long before the close of the Upper Devonian. The most marked orogeny of the Arbuckle Mountains took place, not at the close of the Pennsylvanian, but considerably earlier, namely, toward the close of Canyon time, as anyone may see by studying carefully George D. Morgan's work on the "Geology of the Stonewall Quadrangle, Oklahoma."[5] The folding of the Wichita Mountains in the same State came later. Lee tells us that the Ancestral Southern Rockies arose before the close of the Pennsylvanian, but how long they continued to rise is not yet known. The Cobequid Mountains of Nova Scotia were folded or elevated early in Westphalian time and again before the close of the Pennsylvanian. In western Europe the Paleozoic Alps had their main orogenic movement in the Upper Carboniferous long before the close of the Coal Measures. The Appalachians began to rise late in the Pennsylvanian, and at what time they attained their climax of ascension

[5] Bull. 2, Oklahoma Bureau of Geology, 1924.

in the Permian no one knows. In the Glass Mountains of western Texas intense folding took place early in the Pennsylvanian, apparently at the close of Bend time, or at least before the close of middle Coal Measures time. The Laramide deformation has two or more times of movement, and, according to our present correlation, one is at the close of the Mesozoic and the other in the early Cenozoic. Finally, in the Cenozoic, mountains were rising somewhere in the world from late Eocene time on into the Pliocene, and in California even the Pleistocene strata are deformed. These facts should, it would seem, forever dispel the idea that diastrophism alone can be depended on to fix the boundaries of systems or even of eras.

Boundary between Ordovician and Silurian

On the other hand, the paleogeography and the cycles of sedimentation of the formations on either side of the Taconic orogeny are also not alone in themselves decisive in fixing an unmistakable and clear boundary between the strata of the "Ordovician system" and those of the Richmond series. We are, therefore, again dependent mainly on the fossils, for, after all, paleontology is the primary basis in correlation and historical dating. Our biologic conclusions must, of course, be checked by the stratigraphy, the paleogeography, and the diastrophism.

Regarding the paleontologic evidence for closing the Ordovician, I agree with the conclusions of E. R. Cumings and J. J. Galloway published in 1912.[6] They say:

> "We believe that the Richmond is most intimately associated with the subjacent Ordovician, both lithologically and faunally, and that it should be retained in the Ordovician system."

This conclusion is abundantly backed up by the faunal statistics, and these, according to W. H. Shideler,[7] show that "14 per cent of the 395 Maysville species lived on into the Richmond, while not one of the 494 Richmond species lived on into the Medina or Clinton."

In 1914 Ulrich said:

> "There can be no doubt regarding the actuality of the physical break between the Richmond and the Albion groups of the Medinan series,"

and then he adds:

> "But it is not of the kind that marks stratigraphic boundaries separating distinct systems."

[6] 37th Rept., Dept. Geol. Nat. Res. Indiana, 1912 (1913), pp. 353-478.
[7] Science, March 17, 1916, p. 396.

With this verdict I disagree wholly, and the same is true of most geologists. Ulrich's Silurian system is delimited below at "the break between the Maysville and the Richmond and between their correlates."[8] I am not at all certain that this break exists between these two sets of formations in the Ohio Valley, but even if it is present, I would not regard it as indicating the beginning of the Silurian.

In this connection we should not forget that the boundary between the Ordovician and the Silurian must first be adjusted on the basis of the strata and faunas in Wales, the type area for these two systems. On the basis of fossils, this boundary has never been clearly defined; and yet, so far as I know, every European stratigrapher places the correlates of our Richmond in the Ordovician, among them the Borkholm of Esthonia, the Leptæna, Trinucleus, and Dalmanites beds of Sweden, and the upper Hartfell of Scotland. Doctor G. T. Troedsson, of Lund University, has studied these faunas and, after seeing our American equivalents, believes himself justified in concluding that, "on account of the graptolite fauna, we must place the Richmondian at the top of the Ordovician."[9]

Conclusions

(1) The long known, but now seemingly restricted, diastrophism beginning toward the close of Maysville time is not thought to be so important as the later one, which brought on the widespread emergence toward the close of the Richmondian—a break of long duration, as is attested by the markedly dissimilar succeeding faunas of Alexandrian time. Therefore it is held that the geologic and paleontologic evidence, when taken all together, is in favor of placing the boundary between the Ordovician and Silurian at the top of the Gamachian series, and where this is absent, at the top of the Richmondian.

(2) Should we Americans break away from European standards and conclusions and set up our own standards of correlation, then, for the sake of better harmony, we should agree to close the Ordovician (= Champlainian) with the Maysville, beginning a new period with the Richmond and closing it with the very widespread post-Gamache emergence. We might agree to call this period Anticostian, restricting Billings's term to the formations beneath the Becsie River. The Silurian would then begin with the upper Medina or Alexandrian series, just as our geological literature has been teaching for about seventy-five

[8] Compte Rendu, 12th Internat. Geol. Congress, p. 651.
[9] Med. Lunds Geol. Fältklubb, ser. B, no. 12, 1921, p. 18.

years. If, then, the geologists of other countries will not recognize the Richmond-Gamache formations as a system, but prefer to regard them as constituting an epoch, well and good; at least, they will be able far more easily to understand us than they will be if we extend their Silurian downward to include the Richmondian and its equivalents.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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COUTCHICHING PROBLEM[1]

BY FRANK F. GROUT

(*Presented in abstract before the Society December 30, 1924*)

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INTRODUCTION

In the attempt to correlate areas of pre-Cambrian rocks the greatest difficulties arise in bridging gaps occupied by intrusive granite. Such a gap has separated the Huronian rocks of the Vermilion iron-bearing district in Minnesota and the series of rocks on Rainy Lake (see figure 1). For several seasons the Minnesota Geological Survey has been at work in this area, and the conclusion has been reached that the mica schists of the altered Knife Lake slates, shown by the United States Geological Survey as Lower-Middle Huronian, are equivalent to the mica schists shown by Lawson on Rainy Lake as Coutchiching. Before stating such a conclusion, however, the Survey has felt it necessary to restudy certain critical areas and do detailed work at certain places on the problems involved. This can now be reported. The paper has been critically read by the members of the Survey staff and by Doctor C. K. Leith, and their suggestions are here gratefully acknowledged.

Anyone not familiar with the intricacy of Lake Superior structure might wonder why it has taken so long to reach conclusions as to the

[1] Manuscript received by the Secretary of the Society December 31, 1924.

succession in such a well exposed area as Rainy Lake. The rocks there are closely folded, most of them steeply inclined and schistose, with their original textures pretty well masked by the extensive structural and metamorphic changes which they have undergone. Only the most detailed field-work can straighten out the succession. The new results here reported come mainly from determining the tops and bottoms of the highly metamorphosed sedimentary beds by means of cross-bedding and change in grain. The evidence from this source is abundant and conclusive and requires a radical change in older sections which were based on broad field relations and apparent generalized attitudes and which did not take into account the details of close folding.

The Problem

It has been stated that a series of sediments (mica schists) on Rainy Lake lie below the lava flows of the Keewatin.[2] Lawson has named the sediments of this lower formation the Coutchiching and has described their petrographic nature in sufficient detail.[3] He believed that these rocks existed in large volume, that they constituted the oldest known sedimentary series, and that they should receive an important place in any general classification of the pre-Cambrian. While this view has not been accepted by the United States Geological Survey and some of the Canadian geologists, it has received noteworthy recognition in many textbooks and reports.

Lawson's main evidences of the position and relations of the Coutchiching lie at Rice Bay, on the Canadian shore of Rainy Lake, where a batholith of granite gneiss, supposedly Laurentian, is encircled by mica schists of sedimentary origin and these by hornblende schists, supposedly Keewatin. The encircling formations dip away from the granite steeply, and it is certain that some biotite schist which is of sedimentary origin lies below the hornblende schist of Rice Bay. Certain questions may arise, however, as to the age of both formations, as suggested below.

Lawson, in 1885, mapped the Coutchiching beds as including immensely greater masses on the south shore of Rainy Lake, in Minnesota. The mapping was found faulty by a special committee from Canadian and United States Geological Surveys in 1905.[4] Lawson,[5] in 1911, re-

[2] A. C. Lawson: Geology of the Rainy Lake region. Am. Jour. Sci., vol. 33, 1887, p. 477.

[3] The composition as well as the field structures show that most of the schist is sedimentary, contrary to a suggestion by Steidtmann in Bull. Geol. Soc. Am., vol. 31, 1920, p. 144.

[4] Journal of Geology, vol. 13, 1905, p. 95.

[5] A. C. Lawson: The Archean geology of Rainy Lake restudied. Can. Geol. Survey Memoir 40, 1913.

studied the area for the Canadian Survey and reaffirmed his belief in a sedimentary formation below the Keewatin. Since then he has been at complete disagreement with other geologists as to the Minnesota exposures.

Minnesota Shore of Rainy Lake

Figure 2 is a map and section of one of the critical areas on the Minnesota shore of Rainy Lake. The belt of mica schists which outcrops along

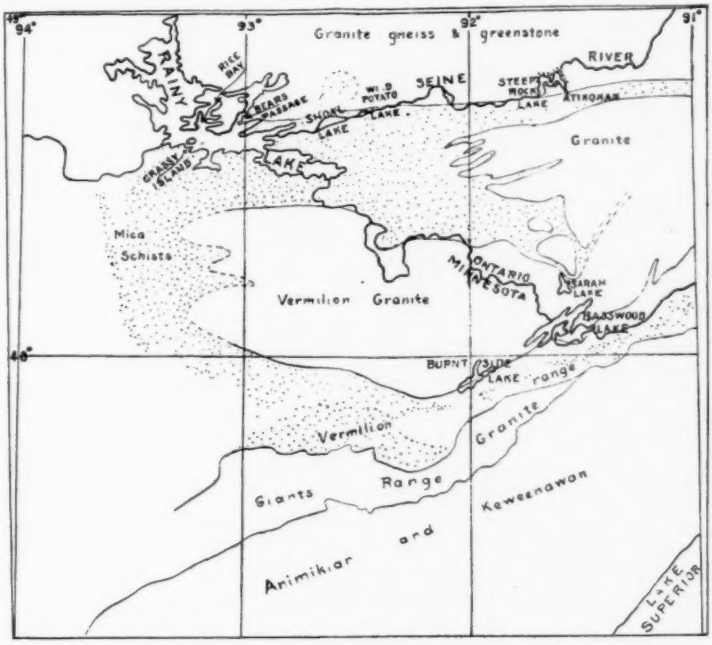

FIGURE 1.—*Key Map to the Districts referred to in this Paper*
Some Huronian areas stippled.

most of the south shore, formerly mapped as Coutchiching, is interrupted by other formations from Rat Root Bay to Black Bay. These include Keewatin green schists with their characteristic ellipsoidal structure, Laurentian granite gneisses, and a series of Huronian sediments grading from conglomerate and arkosites to schists. The formations can not well be correlated by petrography alone, for there are two green schists, two conglomerates, and probably two mica schists. The rocks are evi-

dently part of a belt traced by outcrops on the islands for a long distance east. The belt has been interpreted as a syncline,[6] but our detailed study indicates that it is an anticline, as shown by the sections in figure 2. The reasons for this change should be noted.

Two exposures of conglomerate, in addition to those shown by Lawson, are found on Grassy Island—one north and one south of the Keewatin and Laurentian core of the island. This distribution of conglomerate, on both sides of rocks that are agreed upon as Archean, at once suggests an anticline, though the north limb is intruded by granite and is evidently a thinner bed of conglomerate than the south limb.[7]

Two conglomerates outcrop on Neil Point, with arkose sand between them and green schists outside of them. Lawson correlates the two conglomerates and thinks the green schists connected. The structures, however, can be determined with perfect certainty by the cross-bedding in the arkose. Figure 3 was sketched from the south side of Neil Point, near the conglomerate. The tops of the beds in and near the conglomerate are on the south side, and the position of the beds is the same all across the point and the islands east of it. It is clear that pebbly beds occur at two horizons in the Huronian and the conglomerate on the south side of Neil Point overlies the arkose.[8]

The green schists, one south of Neil Point and another north, on Grassy Island, also differ enough to make their correlation questionable. On Grassy Island there are green ellipsoidal lavas; south of Neil Point there are only relatively thin sedimentary green schists, which may be found grading into conglomerate; for example, on the section line between sections 31 and 32, township 71 north, range 22 west. Evidently the green schist south of the Point overlies the two conglomerates and is Huronian, whereas that on Grassy Island is Keewatin.

This conclusion, that the structure of Grassy Island is anticlinal, indicates that the mica schist on each side is a younger formation than the Huronian conglomerate. It cannot be maintained that the schist is older on account of its great metamorphism, because there are exactly similar schists interbedded with the conglomerate which is accepted as Huronian. They may be seen, for example, on the east side of Frank Bay.

A second argument confirming the Huronian age of the mica schists is

[6] A. C. Lawson: Op. cit., p. 69.

[7] It is possible that some of the difficulties encountered in mapping may be due to faults, but only very small faults have been seen. A shift of formations is indicated along the diabase dike on Grassy Island.

[8] In this respect it is like the Huronian sediments in the Vermilion district. The Ogishke conglomerate at the base is variable and there are several pebbly lenses in the Knife Lake slate above.

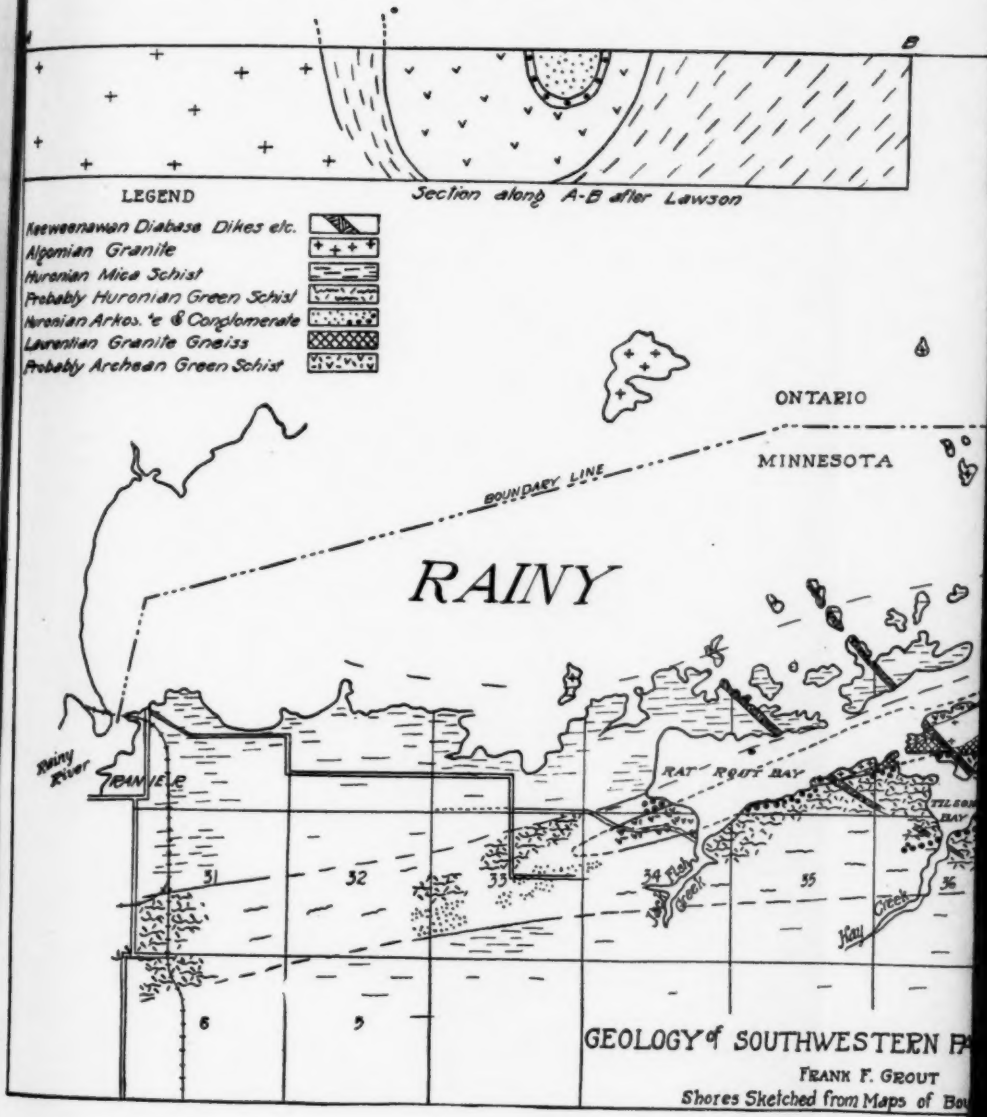

FIGURE 2.—*Geology of southwest*

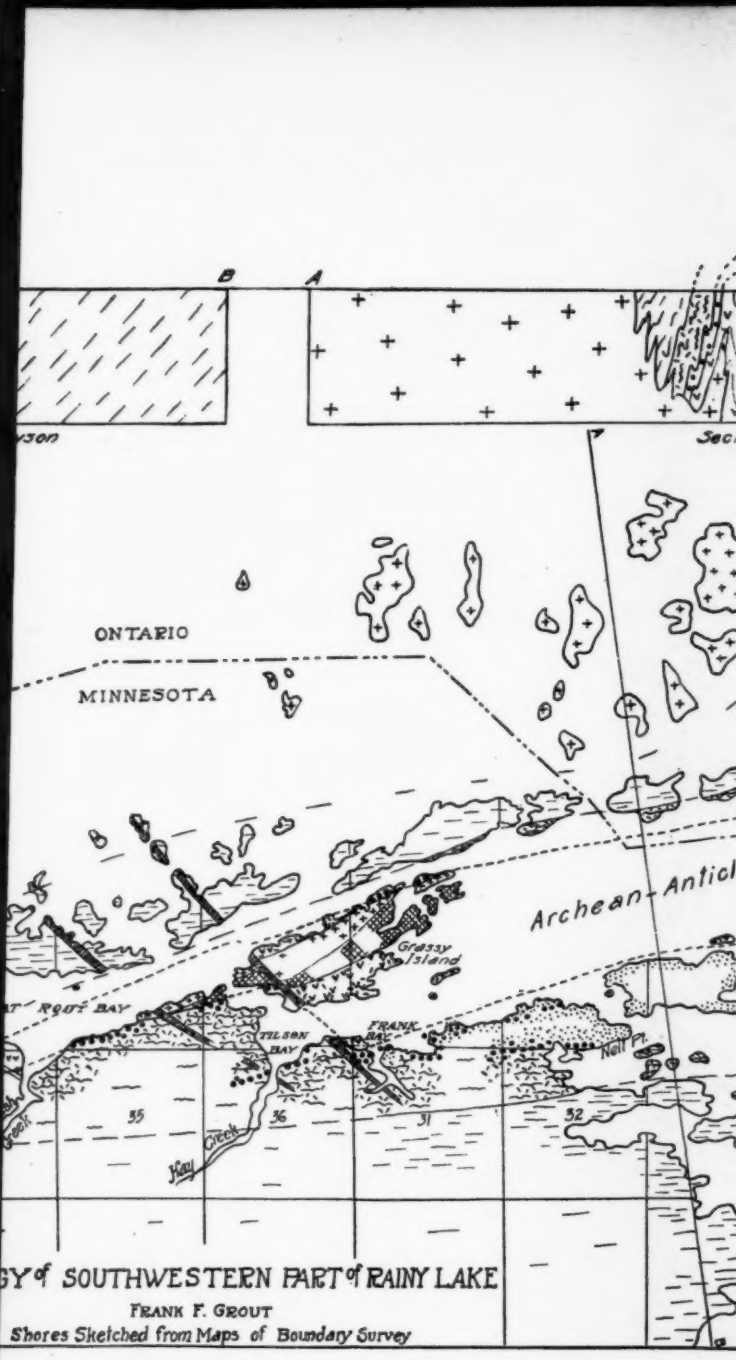

FIGURE 2.—*Geology of southwestern Part of Rainy Lake*

B
Section along A-B revised
SWELL BAY
SAND POINT ISLAND
Capstan Rock
LAKE
Axis
Anticlinal
DRYWEED ISLAND
34
35
36
BLACK BAY
Co. line

based on the approximate continuity of schists from the Knife Lake schists at Burntside Lake (see below) to Rainy Lake. Through the mass of the batholith, in three-fourths of the outcrops, there are many biotite schist inclusions. There is little hornblende schist and little granite without inclusions. The biotite schist formation must have been a very extensive one. On looking over the region for such formations, it is clear that the Knife Lake slate is the only large one available, the Coutchiching being small, if it really exists, in the most promising area on Rice Bay. The correlation across the granite can scarcely be doubted. Since this formation is considered Huronian[9] and extends nearly to the west side of Rainy Lake, it is clear that at the type locality of the Coutchiching no formation should be considered older than the Keewatin.

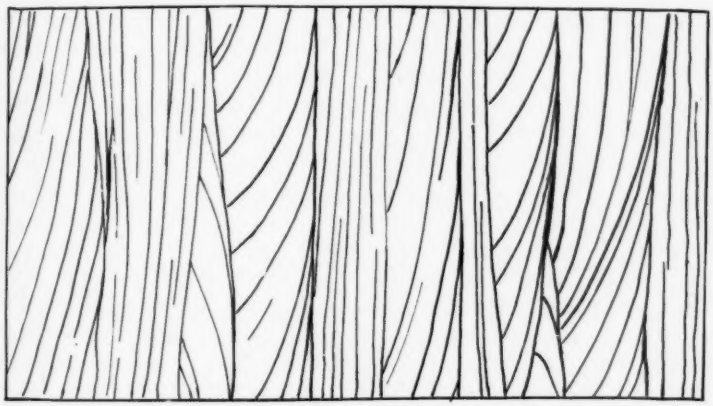

FIGURE 3.—*Cross-bedding sketched from Exposures on the south Side of Neil Point*

Tops of the beds are on the left (south).

Finally, it has been noted that mica-schist pebbles occur in the basal conglomerate of the Huronian series, both here and elsewhere in Minnesota. These, however, are not to be considered as much evidence of a pre-Keewatin sediment. The pebbles of mica schist are few in comparison with others. They may be derived from rhyolites in the Keewatin, which are altered (even here on Grassy Island) to mica schists; and if they should prove to be of sedimentary origin, they may be part of some earlier Huronian series or some schist interbedded in the Keewatin series.

This insistence that the pre-Keewatin age of mica schists has not been

[9] It has heretofore been classed as Lower-Middle Huronian, but reasons are to be given elsewhere for considering it Middle Huronian.

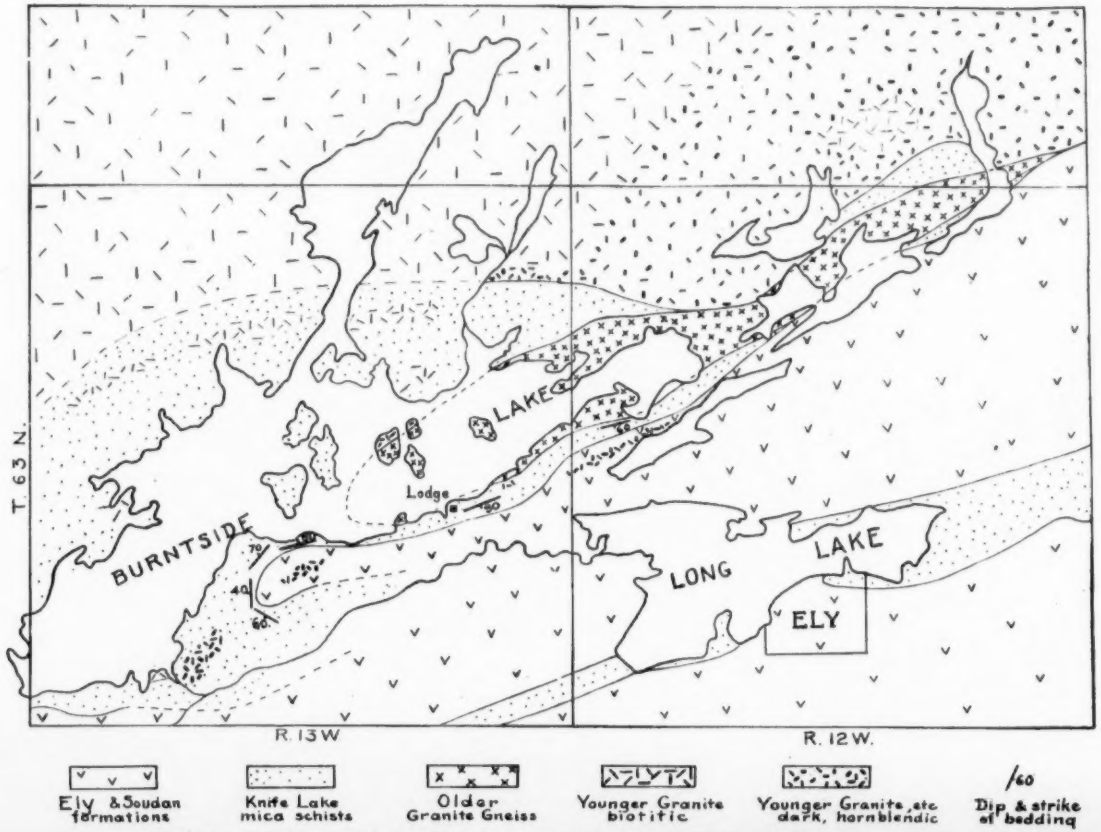

FIGURE 4.—*Geology of the Burntside Lake Area, Township 63 North, Ranges 12 and 13 West*

The mica schist south of the east end of Burntside Lake dips under Ely greenstone, but is clearly overturned. This schist is continuous to outcrops southwest of the center of township 63 north, range 13 west, where the schist overlies greenstone. See page

proved naturally is not a proof that such sediments are absent, but it makes it undesirable to give such a hypothetical series any prominence.

Burntside Lake Area

Only one other area in Minnesota has so far offered us a suggestion of a formation older than the Keewatin greenstone. This is at the east end of Burntside Lake, on the Vermilion iron range.[10]

In this area two granite masses intrude a folded complex of Keewatin greenstone and Huronian mica schist. One of the granites looks old and gneissic, the other fresh and unaltered. The younger one is filled with inclusions of mica schist, while the older one has very few inclusions. This might suggest that the older granite formed before the accumulation of the sediment, which furnished the abundant inclusions in the later granite—in other words, before the Huronian schist. Such a line of argument would make the older granite seem to be Laurentian.

Furthermore, the older granite south of the east end of Burntside Lake intrudes a thin mica schist which dips under greenstone, as shown in figure 4. If the granite is Laurentian, the older schist dipping under greenstone might well be supposed to be Coutchiching.

It should be noted, however, that the basis of this line of argument is mostly petrographic—the alteration of the older granite and the inclusions in the younger granite. It can be shown by structural mapping that the conclusions are erroneous. The alteration of the gneiss is probably a result of its intrusion by a later granite, not of any great difference in age. The lack of inclusions in the older granite may be a result of its relatively small mass and consequent lack of ability to stope its roof.

The correct structure is probably that shown on the map, figure 4, where it may be seen that the schist that dips under greenstone at the east end of the lake can be traced southwest in a continuous belt to a place where it is folded over a Keewatin anticline. It is clearly younger than the Keewatin.

In summary, the evidence of the Minnesota outcrops thus far observed is that the Coutchiching does not deserve a distinct formation name. A pre-Laurentian sedimentary formation is indicated only by some small beds of aluminous sediment in the Keewatin greenstone, and, even less

[10] Winchell once referred to Coutchiching on Burntside Lake, but later decided the schists were younger than Keewatin. (See vol. IV, Final Report.) This was criticized by Lawson. Am. Jour. Sci., vol. 9, 1900, p. 151. Clements, in U. S. Geol. Survey Mon. 45, 1903, p. 160, strongly contends that no Coutchiching occurs in the district.

definitely in a few places, by pebbles in the conglomerate at the base of the Huronian slate.

Canadian Localities

Bears Passage Area

On the north shore of Grassy and Review islands (figures 1 and 2) are some exposures of conglomerate which are the basis of our conclusion that the main structure of the islands is anticlinal. If this is correct, the green schist and mica schist just north of these islands in Canada are to be classed as Huronian just as certainly as those south of Neil Point. This area of mica schist is practically continuous with one of the large areas interpreted by Lawson as Coutchiching—that at Bears Passage, a few miles northeast of Grassy Island, where Anglomian granite is encircled by schists. Observations supporting our claim that these are Huronian may be cited in considerable number, though no great amount of time was devoted to the field.

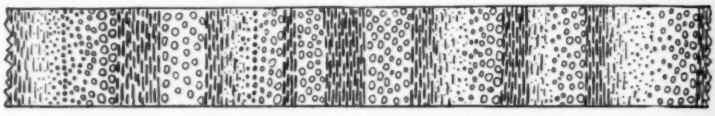

Figure 5.—*A Series of sandy Shale Beds on Morton Island of Rainy Lake*

Section shown is 15 inches long. The beds are vertical, but the tops are clearly to the left (north).

(*a*) A conglomerate (though a thin one) is visible on Sand Point Island in a position similar to that on Grassy Island.

(*b*) Lawson himself noted a conglomerate at the east end of Swell Bay which may be correlated with these.

(*c*) Finally and most conclusively, the mica schists south of Bears Passage on Morton and Dude islands show, by the gradation of grains in successive beds (figure 5), that the tops of the beds are to the north. They do not dip under the greenstones that lie just south of them, but lie above the greenstone and dip north, toward the granite. This quite eliminates the supposed anticlinal structure of the belts near Bears Passage.[11]

Belt from Minnesota Shore of Rainy Lake up the Seine River

Lawson has traced the Huronian conglomerate (which he names as part of the Seine series) from the Minnesota shore of Rainy Lake eastward to Sabawe Lake, a stretch of 60 miles (see figure 1). Through this

[11] A. C. Lawson: 12th Int. Geol. Congress, 1913, p. 422.

area deformation has tilted it steeply, but in general left it bordering the south side of older folded rocks, with a contact that shows only broad, sweeping curves. It is important in this connection to note the relation of this conglomerate to the mica schist south of it. On Shoal Lake (just east of Rainy Lake) there is a syncline of Huronian sediments, south of which is a little clearly ellipsoidal Archean greenstone. Then comes another Huronian belt of arkosite. This second belt seems to have a continuous dip to the south. The tops of the beds can be located in the arkosite and even in the green schists, and the structure can be clearly shown in scores of places. Along Wild Potato Lake, east of Shoal Lake, a great thickness of sandy beds stands vertically, but all have their tops to the south. From several of the conglomerate outcrops mentioned in

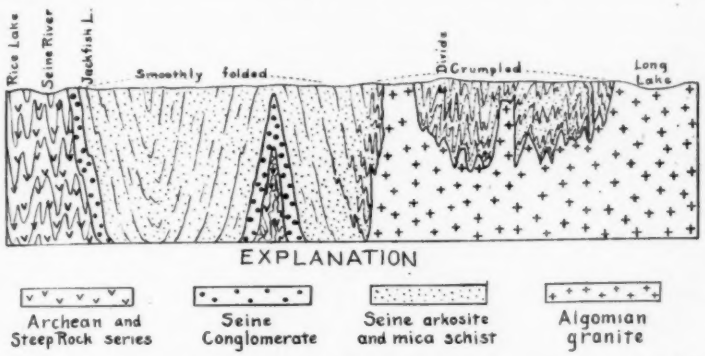

FIGURE 6.—*Geologic Section from Rice Lake to Long Lake, southwest of Atikokan, Ontario*

Lawson's restudy[12] a double fold can be detected by a short traverse south. The easternmost one visited in our work is so similar to the one on Rainy Lake that the essential continuity of the fold may be assumed until detailed work can be done (see figure 6). All the area of mica schist from the Seine conglomerate south is thus presumably Huronian—a part of the Seine series.

A further argument that the mica schist south of the Seine River is Huronian may be based on exactly the sort of evidence that Lawson uses to show the age of the conglomerate. The conglomerate transgresses the sharply folded greenstone and the Lower Huronian Steep Rock series in a gently undulating belt trending nearly east for about 60 miles. The difference between this simple structure and the crumpling in the older

[12] Op. cit., pp. 64-65.

beds is good evidence that the conglomerate is younger than the Steep Rock series. Now, the conglomerate belt is perfectly conformable with the arkosite and mica schist south of it, as can be seen by anyone who crosses the series in a few places. The mica schist, though formerly mapped as Coutchiching, is, therefore, as young as Huronian and is perfectly continuous with the mica schist in Minnesota.

RICE BAY AREA

Finally, a word is needed as to the rocks on Rice Bay, in which Lawson seems to find the strongest evidence of a Coutchiching formation below

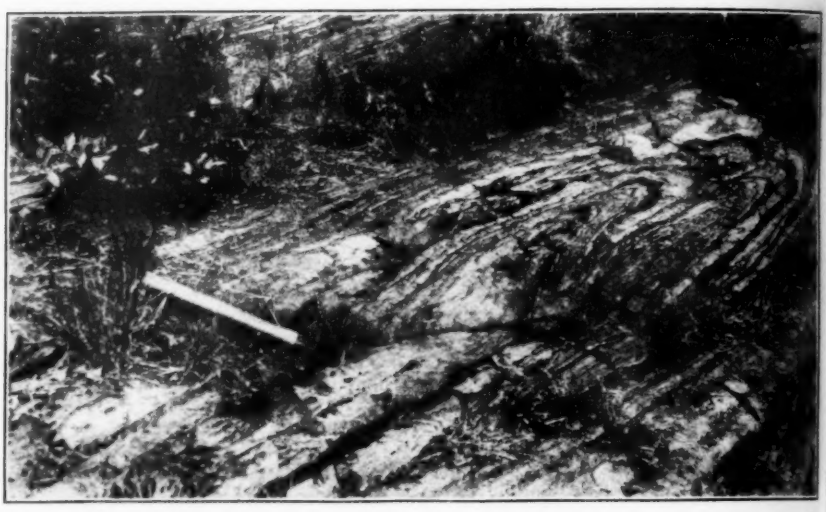

FIGURE 7.—*Close folding in the Mica Schist on Rice Bay of Rainy Lake*

the Archean greenstone. It has already been admitted that some mica schist there dips under hornblende schist as if it was an older sediment, but it is doubtful whether even this is a Coutchiching formation. Several questions should be answered before the formation should be considered as established.

A. Can not the hornblende schist and mica schist both be Huronian? The hornblende schist has not the peculiar ellipsoidal structures so characteristic of Keewatin elsewhere,[13] and the Huronian has been shown to have green schists associated with the biotite schists.

[13] The rock called ellipsoidal and analyzed for Lawson's report, page 50, was found to be an intrusive breccia rather than an ellipsoidal flow.

B. Is it not possible that the biotite schists and hornblende schists are folded and overturned? Close folding is visible in the schists around Rice Bay (see figures 7 and 8). No evidence has been given that the beds are not overturned, and their petrographic characters are not such as to show their structure.

C. Is there enough of the biotite schist anywhere below the greenstone to deserve a formation name? Lawson maps the belt as nearly half a mile wide and estimates a considerable thickness (though much less than his estimates of the thickness in Minnesota). This is uncertain.

FIGURE 8.—*Close folding in the Mica Schist at Ranier, Minnesota*

This is the type locality for the supposed Coutchiching formation, near the head of Koochiching Falls.

(1) The underlying granite is altered to mica schist near its borders and Lawson puts the base of the sediment too low in some places.

(2) The gradation to hornblende schist also shows alternations, and Lawson puts that contact rather high.

(3) The beds are repeated in places by folding, as shown in figure 7.

(4) Finally, the area he maps is far from being dominantly biotite schist. Continuous exposures across the whole series could not be found, but the best exposure for study is that east of the channel entering Rice Bay. Here a measurement of 1,250 feet across the strike shows

28 per cent sedimentary biotite schist,
22 per cent aplitic intrusive,
34 per cent porphyry and granite gneisses,
12 per cent green schist.

Other less complete sections show a still larger ratio of green schist. If we eliminate later intrusives, the formation is evidently small. If the thickness is reduced to allow for folding, intrusions, and errors in mapping, the Coutchiching becomes a series of thin beds, possibly 500 feet in the aggregate, such as might be interbedded in the Keewatin greenstone. At the top it grades by alternation into greenstone, greenstone occurs in the midst of it, and, since no conglomerate base is known, it seems likely that it originally had greenstone below as well as above, and deserves no formation name indicating a lower stratigraphic position.

Conclusion

Notwithstanding the suggestiveness of the Rice Bay area, the claim for a Coutchiching formation has little to support it. The name is not to be favored until detailed work on Rice Bay or some other area has gone much farther than at present. The Keewatin greenstone remains "the oldest known rock."[14]

Discussion

Prof. Andrew C. Lawson: I have listened with deep interest to Professor Grout's statement of the results of his studies of the Archean of Rainy Lake and desire to discuss briefly his proposal to abolish the Coutchiching. We make progress in geology, and particularly in Archean geology, by the correction of errors; and I do not claim to be infallible in a field so difficult to unravel. It may be that I have included in the Coutchiching rocks of another group, and if that be so I shall be glad to have the correction made. It is becoming more and more apparent that, notwithstanding their metamorphism, the rocks of the Archean are amenable to ordinary stratigraphic methods, and that detailed mapping brings out the true relations of these ancient formations, while reconnaissance methods lead very often to misconceptions. But while it may be conceded, as a result of Professor Grout's observations, that the area mapped as Coutchiching on the south side of Rainy Lake possibly includes later rocks, the evidence is clear that below the Keewatin there is a body of metamorphosed sedimentary strata several

[14] N. H. Winchell: The oldest known rock. Am. Geol., vol. 22, 1898, pp. 262-263.

thousand feet thick, a real stratigraphic entity, to which the term Coutchiching properly applies.

At the Bears Passage on Rainy Lake there is exposed on the line of the Canadian Northern Railway and on the adjacent lake shores the anticline shown in the accompanying figure 9. The exposures are almost continuous and the structure is clear. The Coutchiching rocks are well stratified and observed dips are numerous. The strata in the central part of the anticline lie flat and the angle of dip increases toward both flanks, where the Coutchiching beds pass down under the Keewatin. The distance between the overlying Keewatin on the east flank and that on the west is about two miles, and in the intervening anticline there is a duplicate exposure of about 3,000 feet of Coutchiching strata consisting of mica schists and paragneisses. Professor Grout states that

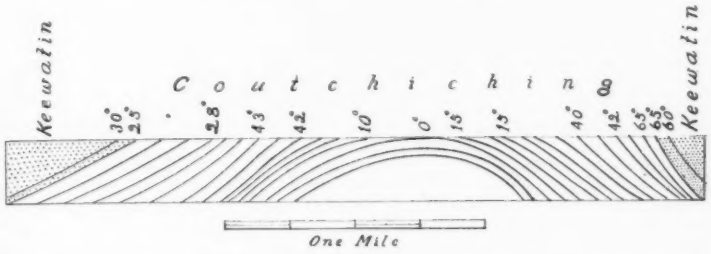

FIGURE 9.—*Showing stratigraphic Relations of Coutchiching and Keewatin in the Bears Passage Anticline, on the Line of the Canadian Northern Railway, Rainy Lake*

the individual beds of the Coutchiching grade from coarser to finer in the thickness of each bed, and that, according to the rule that coarser material should be at the bottom of the bed, my section is upside down. I question the universality of the rule. I would accept it as indicative of a certain type of sedimentary process; but that all sedimentary beds grade upward in fineness of grain is pure hypothesis. The anticline at the Bears Passage and the relationships which it so clearly exhibits are easily accessible both by train and by canoe, and the structure there observable is much more reliable evidence of the sequence of formations than the hypothesis of gradation of texture in individual beds.

Professor GROUT (answering Professor Lawson): Doctor Lawson's observations along the railroad near Bears Passage will, of course, not be questioned. The mica schist, however, in that section is so far recrystallized that the top and bottom of the original beds can hardly be determined. In most of the district overturned folds are common, and in

every case where we found the mica schist retaining structural evidences of the top of the beds the only beds under greenstone were overturned.

South of the Bears Passage granite the structure is clear and the schist is younger than greenstone, as determined by the gradation of grain. This criterion, while possibly not uniformly acceptable to all geologists, is very conclusive when a large number of successive beds all indicate uniformly the same side of the series of beds is the top of the formation.

I have not visited the Lake of the Woods and have been much interested in their reports indicating sediments older than Keewatin. The structural and areal work may there be more convincing than it is at the original and type locality.

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EROSION IN SAN JUAN CANYON, UTAH[1]

BY HUGH D. MISER

(*Presented before the Society December 29, 1924*)

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PRESENT INVESTIGATION

The San Juan Canyon, through which San Juan River runs, extends west across a high arid region in southeastern Utah and joins Glen Canyon of the Colorado near the southern boundary of the State. In 1921 I was attached as geologist to an engineering party which explored and mapped the San Juan Canyon for power and storage projects. The seven men comprising the party were under the leadership of K. W. Trimble, topographic engineer of the United States Geological Survey. They embarked on the canyon voyage in two small open rowboats on July 18 and reached Colorado River on October 3.

The journey of the Trimble party through the steep-walled chasm revealed a magnificent geologic structure section possessing the same dimensions as the canyon—133 miles long and as much as half a mile high. Although the vividly colored walls thus displayed the rocks and

[1] Manuscript received by the Secretary of the Society February 2, 1925.
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their structure in minute detail, the greatest interest was aroused by the work of the river, which had carved the canyon and which is still busily engaged in eroding rocks and transporting their debris. Interest in this subject was not mildly created, but was forcibly excited by hourly experiences in navigating the swift, muddy torrent between close towering walls, which for long distances would rise sheer from the water's edge.

Our voyage was the first to be made by an engineering party and the canyon had not been mapped previously. Three expeditions of prospectors had preceded us, but, in spite of the information furnished by them or other persons, we did not know in advance whether we would have to travel 100 or 150 miles to reach the Colorado. There are comparatively few reports on the region, the most comprehensive reports being those by Woodruff,[2] Gregory,[3] and Pierce;[4] but the principles of erosion, so clearly set forth by Powell, Gilbert, Dutton, and others, who describe adjoining areas, apply equally well to the country crossed by San Juan Canyon.

The present paper is abstracted in part from a detailed reconnaissance report on the geography of the region which has been published as Water-Supply Paper 538 of the United States Geological Survey. A fuller discussion of the age and correlation of the rocks is given in Professional Paper 132[5] and a description of the geologic structure is given in Bulletin 751.[6]

Region crossed by Canyon

The region crossed by San Juan Canyon is a part of the Colorado Plateau which is characterized by canyons, cliffs, mesas, and buttes. The general upland surface, ranging from 5,000 to 6,000 feet above sealevel, consists of several plateaus or platforms, which are arranged in a great geologic stairway (see figure 1). The plateaus are floored by hard rocks and have been stripped free from soft rocks, which are exposed in the escarpment of the next higher plateau. The only mountain standing near the San Juan in Utah is the solitary peak of Navajo Mountain, which rises to an elevation of 10,416 feet.

[2] E. G. Woodruff: Geology of the San Juan oil field, Utah. U. S. Geol. Survey Bull. 471, 1912, pp. 76-104.

[3] H. E. Gregory: The San Juan oil field, Utah. U. S. Geol. Survey Bull. 431, 1911, pp. 11-25. The Navajo country. U. S. Geol. Survey Water-Supply Paper 380, 1916. Geology of the Navajo country. U. S. Geol. Survey Prof. Paper 93, 1917.

[4] R. C. Pierce: The measurement of silt-laden streams. U. S. Geol. Survey Water-Supply Paper 400, 1917, pp. 39-51.

[5] C. R. Longwell, H. D. Miser, R. C. Moore, Kirk Bryan, and Sidney Paige: Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona. U. S. Geol. Survey Prof. Paper 132, 1923, pp. 1-23 (Prof. Paper 132-A).

[6] H. D. Miser: Geologic structure of San Juan Canyon and adjacent country, Utah. U. S. Geol. Survey Bull. 751-D, 1924.

The roughness of the region, the meager rainfall, the almost total absence of soil, and the scantiness of vegetation make it a desert waste, practically all of which reveals bare rock ledges. The predominating colors in any landscape are buff, brown, and red. The canyon is nearly inaccessible. The upper part, which lies 175 miles from railroad, can be reached at a few places by roads, but the lower part, which is 200 to 250 miles from railroad, can not be reached except by boat down the river or by pack train over poor trails.

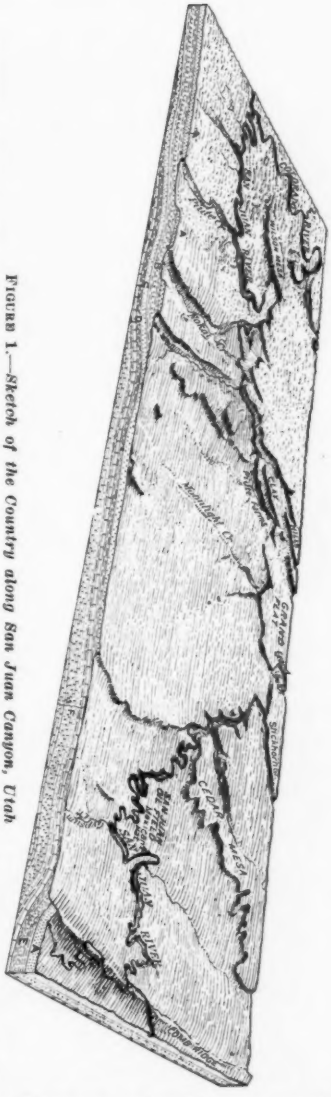

FIGURE 1.—*Sketch of the Country along San Juan Canyon, Utah*

Showing a vertical section in front, with a landscape beyond. A, Navajo sandstone, Todilto (?) formation, and Wingate sandstone, of Jurassic age; B, Chinle formation, Shinarump conglomerate, and Moenkopi formation, of Triassic age; C, Coconino sandstone; D, Supai (?) formation, both of Permian age; E, Chinle, Shinarump, Moenkopi, Coconino, and Supai (?) formations; F, Goodridge formation of Pennsylvanian age.

THE ROCKS AND THEIR INFLUENCE ON FEATURES OF CANYON

Igneous rocks are nowhere exposed in the canyon, but are found at a few localities in the adjacent country, where they include dikes and volcanic necks of Tertiary age. The sedimentary rocks, which are thus the only rocks revealed in the cross-section in the canyon, consist of 5,000 feet of limestone, sandstone, and shale of Pennsylvanian, Permian, Triassic, and Jurassic ages. They are arched into a broad dome or upwarp whose summit is in the San Juan oil field near the head

of the canyon (see figure 1). From the oil field the rocks dip both upstream and downstream, generally with dips of only a few degrees, though there are several low folds on the slopes of the dome and a small number of faults. The folding of the rocks apparently took place at the end of the Cretaceous period.[7]

Where the river is trenched in hard rocks it runs between close sheer walls that rise directly from the water's edge, and where it is trenched in alternating hard and soft rocks it is joined on either side by a series of vertical cliffs and steep slopes. The river is thus accessible where it is bordered by soft rocks, but inaccessible where it is bordered by hard rocks. The canyon walls and cliffs of the region may frequently be followed for 50 miles or more before a scalable place is found. Such places are most numerous where the rocks are cut by faults and by numerous close joints.

The structure of the rocks has had little or no influence on the course of the river, for the river runs west directly across anticlines, synclines, and monoclines which involve both hard and soft rocks, and the bends of the river bear no relation to faults and joints. This, as will be explained below, is apparently due to the inheritance of the present course from a crooked course on a former peneplain or on a cover of beds of Tertiary age.

Age of Canyon

The river, regardless of the fact that it runs through a chasm as much as half a mile deep, is very crooked and has numerous meanders or goosenecks. The distance it runs in the canyon is 133 miles, yet the distance in a straight line is about half this, or 63 miles. The present course, as has already been pointed out by Gregory,[8] appears to be a striking example of an entrenched meandering stream from a former peneplain. The original course, as has also been pointed out by him, was possibly on beds of Tertiary age which rested with angular unconformity on the folded Mesozoic and Paleozoic strata.[9] Fragments of a peneplain that stand at an elevation of 5,200 feet above sealevel, or 1,000 feet above the river at the entrance to the canyon, have been observed by me some 20 miles to the northeast, but I do not know the age of it; nor do I know the age of the canyon; but I agree with Gregory,[10] that the conditions

[7] H. E. Gregory: Geology of the Navajo country. U. S. Geol. Survey Prof. Paper 93, 1917, p. 123.
R. C. Moore: Stratigraphy of a part of southern Utah. Bull. Am. Assoc. Petroleum Geologists, vol. 6, no. 3, 1922, p. 223.
[8] H. E. Gregory: Op. cit., pp. 126-127.
[9] H. E. Gregory: Op. cit., pp. 123 and 133.
[10] H. E. Gregory: Op. cit., p. 123.

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FIGURE 1.—VIEW LOOKING NORTHWEST DOWN SAN JUAN RIVER TOWARD MOUTH OF SLICKHORN GULCH

The alluvial cone at the mouth of the gulch is composed of boulders that have been discharged by floods from the side chasm. Photograph by Robert N. Allen.

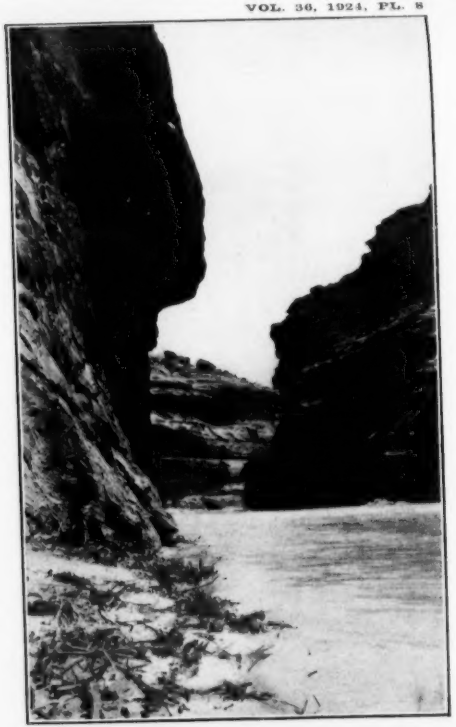

FIGURE 2.—VIEW LOOKING UP SAN JUAN RIVER AT A POINT NEAR THE MOUTH OF MOONLIGHT CREEK

The San Juan is joined by sheer cliffs, but during normal stages runs on sand that has been deposited in a "reservoir" which has been created by the boulder dam at the mouth of Piute Creek, 45 miles downstream. Photograph by Robert N. Allen.

TOPCGRAPHIC FEATURES ON SAN JUAN RIVER, UTAH

for river erosion, which are explained below, are so favorable that only a part of Quaternary time was sufficient for the cutting of the San Juan and near-by canyons. The excavation of the San Juan canyon doubtless took place within the period of the making of the Grand Canyon, about 100 miles to the southwest. Dutton[11] expressed the opinion some 40 years ago that the outer gorge of the Grand Canyon was carved during Pleistocene time, and the inner gorge in Quaternary time. A more recent opinion, by Robinson,[12] places the erosion of the Grand Canyon in the latter part of the Quaternary.

Rapid Cutting of Canyon

Conditions in the region crossed by the San Juan have been favorable for the rapid erosion of a canyon with high, close, steep walls. The river runs across an elevated region, and in passing through the canyon descends from 4,209 to 3,259 feet above sealevel, a total fall of 950 feet in 133 miles, or an average of 7.17 feet per mile; also, the river is perennial, being fed by the snows and rains of the Rocky Mountains and by the thunderstorms of the Colorado Plateau. It, with its steep gradient and resultant great erosive power, has lowered itself faster than the local agencies, assisted by a meager rainfall of 5 inches each year, could lower the adjacent plateau; also, numerous tributaries have hanging valleys. The down-cutting has been rapid, as is suggested by the occurrence of equally steep walls on both sides of the river, especially in the bends. Gentle slopes on the inside of the bend of a stream suggest not only slow downward trenching, but also lateral shifting of the stream's course during trenching.

Pauses of Canyon-cutting

Pauses in the canyon-cutting are indicated by gravel-floored benches or terraces, which are found at a comparatively few places, but the small size of the benches and also their small number suggest that the river was graded for very short periods only.

The benches occur at several different levels up to 600 feet above the river. They are floored by gravel deposits, which are 10 feet or less thick at most places, though at some places they are 20 feet thick, and at a few places are as much as 100 feet thick. The deposits consist of pebbles ranging in size from a small fraction of an inch to cobbles a foot in diameter, the largest lying near the base of the deposits. The pebbles

[11] C. E. Dutton: Tertiary history of the Grand Canyon district. U. S. Geol. Survey Mon. 2, 1882.

[12] H. H. Robinson: A new erosion cycle in the Grand Canyon district, Arizona. Jour. Geology, vol. 18, 1910, p. 763.

are mostly 1 to 3 inches in diameter; they are well rounded, are generally flattened, and are poorly cemented at places by a kind of calcium carbonate known as caliche. They include a great variety of sedimentary, metamorphic, and igneous rocks, and a count of 600 pebbles at a representative locality showed the following kinds of pebbles in the order of their abundance: quartzite, 46 per cent; porphyritic rocks, 32 per cent; flint, 5 per cent; limestone, 4 per cent; granite, 4 per cent; quartz, 3 per cent; gneiss, 2 per cent; schist, 1 per cent; sandstone, 1 per cent; conglomerate, 1 per cent; chalcedony and agate, 1 per cent. The flint, limestone, and sandstone are mostly from rocks exposed in and near the San Juan Canyon, but the quartzite, conglomerate, chalcedony, agate, and the crystalline rocks have been for the most part derived from the San Juan Mountains of southwestern Colorado. Pebbles from these mountains that are now found near the mouth of San Juan River have been transported a distance of 320 miles or more by stream.

Materials of local origin predominate in the deposits that occur at and near the mouths of side streams, and they have all been contributed by the tributaries. In such deposits there are numerous boulders 6 to 8 feet in diameter and one boulder 10 feet in diameter was observed.

Rock Debris on Canyon Floor

General features

Rock debris fills the canyon to a depth of 50 to perhaps 100 feet or more. These depths are suggested by borings on the Colorado at Lees Ferry, Arizona, and also by the partial filling by debris of the mouths of some side canyons along the San Juan (see plate 9, figure 1). The debris along the San Juan not only occurs as small patches skirting the river, but forms the river's bed everywhere, with the probable exception of a few places where inclined ledges of hard rock cross the channel. Such ledges produce rapids and they are presumably swept clear of rock debris by the swift current.

The debris consists of material that is permanently and temporarily deposited, but perhaps no great quantity of material is permanently deposited. Normal stages of the river and small floods only a few feet high are incapable of removing any considerable quantity of material from the river's bed; but high and unusual floods, many years apart, like the one of October, 1911, when the river is said to have reached a stage of 50 feet in the narrower parts of the canyon, remove much of the material under the river's bed, and thus lower the bed during the flood stages. Recent measurements[13] on Colorado River give some idea of the extent

[13] Oral communication from G. C. Stevens, of the U. S. Geol. Survey.

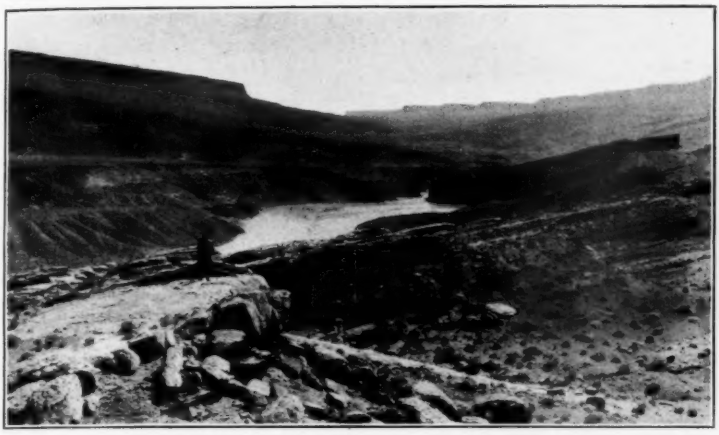

FIGURE 1.—VIEW LOOKING SOUTH DOWN SAN JUAN RIVER TOWARD THE MOUTH OF NOKAI CANYON

The canyon joins the river at base of the dip slope in right center. The San Juan and also Nokai canyons are partly filled with rock debris. Photograph by Robert N. Allen.

FIGURE 2.—VIEW LOOKING DOWN SAN JUAN RIVER AT BASE OF HONAKER TRAIL

The waves, which are "sand waves," are 6 feet or more in height. Photograph by Robert N. Allen.

of scour during floods. The measurements at Lees Ferry and other places where the river's bed is silt show that the area of the cross-section of the scoured debris is equal to or a little greater than the area of the cross-section of the river above normal stage. Other measurements that were made where the river's bed is presumably formed by boulders show that the lowering of the bed by floods is a small fraction of the change in gauge height.

During the recession of the high floods that take place many years apart much of the debris load is redeposited, and thus partly fills the canyon; also, between such floods, much debris, as will be explained more fully under the next heading, is continually being contributed to the canyon by numerous agencies, including wind, rock-falls, landslides, and tributary streams.

The inference from the above statements is that long stretches of the San Juan present most of the time the peculiar example of an alluvial or aggrading stream flowing between close towering walls of solid rock; yet, on the assumption that much of the debris is moved at times of high flood, the river is in reality not an alluvial or aggrading stream, but a degrading stream. To determine whether any of the present debris is or is not a permanent deposit can be settled only by observations over a period of at least a few decades.

SOURCES AND CHARACTER OF ROCK DEBRIS

The debris, including both the deposited material and the material in course of transportation, is derived from several sources. One of the contributing sources is the river's own power of erosion, by which its transported material impinges, wears away, and undermines the canyon walls. Sand swept along the current grinds the wall rocks and grooves them like a sand blast. A chief source of material is the falling or sliding of rock debris from the canyon walls, due to landslides, loosening of blocks by rains, freezing and thawing of water, changes in temperature, and the blasting of rocks by lightning; such debris, which collects as talus at the foot of every cliff, skirts the river for long distances. Sand and dust are brought to the river by the wind, the prevailing direction of which is from the southwest. A part of this material falls into the river and a part is deposited in protected positions on the south canyon wall, where it is piled by the wind into dunes. Fine material is contributed by the sheets of water flowing on the surface during and after rains, and both fine and coarse materials are contributed by every tributary rill and stream. In fact, the material delivered by sheets of water and streams equals or surpasses in quantity that from all other sources combined.

The tributary streams have steep gradients, ranging from 65 feet to more than 170 feet per mile. They are thus able to carry much debris, especially during flood stages. All of them are actively lowering their channels in bedrock, and thus transport their loads of debris to the San Juan; only a part of the load of some streams has been deposited in their channels near the river. The load of debris thus brought to the river includes clay, sand, pebbles, cobbles, mud balls, and boulders. The mud balls are spherical and range in size up to 18 inches in diameter. The rock boulders discharged into the river by the side chasms are large and small. Numerous boulders were observed that are 6 to 8 feet in their longest dimension, several 10 to 12 feet long were observed, and one 18 feet long was observed.

The load of rock debris carried to the San Juan by its tributaries has greatly increased within the last 25 to 35 years. When the region was first visited by white man the tributaries ran on smooth floors of alluvium which they had deposited in their canyons.[14] But some 25 to 35 years ago they began to incise their channels in the alluvium. They at present are eroding and deepening their valleys, and run in inner canyons entrenched in the alluvium or in valleys from which all alluvium has been eroded.[15] This recent incising is thought by Gregory to have been caused by overgrazing and probably, too, by climatic change. Another reason for the change in the character of the valleys of the tributaries is suggested by Reagan, who believes that the former dense population conserved practically all the water by irrigating their fields and by impounding it in village reservoirs. This dense agricultural population, according to him, was replaced by the nomadic Navajo with his stock and by the white man with his roads and trails. The Navajo and white man used little water for irrigation, but let the torrential floods of the streams sweep down the valleys to the San Juan, with their heavy loads of rock debris.

DISTRIBUTION OF DEBRIS

San Juan River, being confined between closely spaced cliffs in most parts of its canyon, does not have alluvial plains in such parts. Whatever alluvial material or debris is present occurs beneath the bed of the

[14] C. E. Dutton: Tertiary history of the Grand Canyon district. U. S. Geol. Survey Mon. 2, 1882, pp. 228-229.

H. E. Gregory: The Navajo country. U. S. Geol. Survey Water Supply Paper 380, 1916, p. 100. Geology of the Navajo Country. U. S. Geol. Survey Prof. Paper 93, 1917, pp. 130-132.

A. B. Reagan: Archeological notes on Pine River Valley, Colorado, and the Kayenta-Tuba region, Arizona. Trans. Kansas Acad. Sci., vol. 30, 1922, pp. 262-267. Recent changes in the Plateau region. Science, new series, vol. 60, 1924, pp. 283-285.

[15] H. E. Gregory and A. B. Reagan, idem.

river and as short, unsubmerged bars. Alluvial plains of small extent occur only in the open stretches, like those near Clay Hill Crossing, Piute Farms, and Zahns Camp. There the river has wide braided channels and narrow alluvial stretches, over which the main channel frequently shifts its position, especially during floods.

In the part of the canyon above the mouth of Moonlight Creek the river runs between walls of hard limestone and sandstone; the fall, or gradient, of the river is high, averaging 8.3 feet per mile; the velocity is great; the canyon fill is mostly coarse debris from adjacent cliffs or from tributary streams; the clay and sand that are brought to the river are not deposited to any great extent, but are carried to the lower part of the canyon or to the Colorado; and the debris is composed in large part of boulders of hard limestone and is thus difficult to transport. This part of the canyon contains more debris than the river can transport during normal stages and small floods; but high floods, such as that of 1911, which attained a stage reported to be 50 feet in the narrower parts of the canyon, may not only move much of the debris, but attack and erode the bedrock. In this stretch the river is confined almost continuously between vertical walls and talus slopes. The boulders of the talus slopes project into the river, and many boulders that are found in the middle of the river are 60 feet long. Such sand as is found occurs as short, low sand bars that skirt the river during low stages, lies among vegetation and boulders, and also forms the river bed. The meager clay in this part of the canyon fills interstices of the coarse rock debris.

Below the mouth of Moonlight Creek the river runs between walls of comparatively soft rocks: the gradient is about 5 feet to the mile: the current is less swift than in the upper part of the canyon; a part of the heavy debris load is deposited; the deposited debris raises the river bed; and the main channel is not only widened at places, but frequently shifts positions on its bed of unconsolidated debris.

Below Moonlight Creek, as well as above it, the mouths of many tributaries are marked by accumulations, or bars, of boulders which have been brought to the river by occasional torrents that sweep down the side chasms (see plate 8, figure 1). Such accumulations along the Colorado have been briefly described by Powell,[16] Gilbert,[17] Dutton,[18] and Davis.[19]

[16] J. W. Powell: Exploration of the Colorado River of the West and its tributaries, explored in 1869, 1870, 1871, and 1872, pp. 82, 83, 97. Washington, 1875.

[17] G. K. Gilbert: Report on the geology of portions of Nevada, Utah, California, and Arizona. U. S. Geog. S. W. 100th Mer. (Wheeler), vol. 3, p. 71. Washington, 1875.

[18] C. E. Dutton: Tertiary history of the Grand Canyon district. U. S. Geol. Survey Mon. 2, 1882, pp. 241-242.

[19] W. M. Davis: An excursion to the Grand Canyon of the Colorado. Bull. Harvard College Museum Comp. Zoology, vol. 38; Geol. Ser., vol. 5, no. 4, 1901, p. 169.

The boulders accumulate at the mouths of the tributaries because the flood-swollen side streams have a greater fall, greater velocity, and at times a greater discharge than the river. Such bars resemble alluvial cones, and not only push the river channel away from the mouths of the side chasms, but produce rapids.

The visible part of the debris deposited at the mouths of tributaries exhibits a gradation from large boulders at the main rapids to pebbles and cobbles downstream. This is especially well displayed at and below the mouth of Piute Creek. The boulder bars built at the mouths of side canyons have the effect of dams, causing slack water above them and also causing the river to deposit part of its heavy load of sand (see figure 2). Although these stretches resemble reservoirs and are filled with sand, the river's current through them is swift and the fall per mile is generally about 5 feet. The longest sand-filled reservoir extends upstream from the first Piute Creek rapid to a point near the mouth of Moonlight Creek, a distance of about 45 miles (see plate 8, figure 2). The boulder dams, with their consequent reservoirs, present a series of steps in the profile of the river.

If a flood in the river should be of sufficient volume to sweep out a boulder bar, it would also begin to pick up and move the sand above the bar, and thus increase the gradient of that part of the river. Floods are known to have partly swept away within the last 30 years the accumulations of boulders at the mouths of Gypsum Creek and Grand Gulch.

QUANTITY OF TRANSPORTED DEBRIS

The quantity of debris carried in suspension by San Juan River is unusually high for streams in the United States. Silt observations which were made by the Bureau of Reclamation near Bluff during a period of 4 months in 1917 show an average silt content of 1.41 per cent by weight, or a little over 1 per cent by volume; but samples taken from the river by R. C. Pierce, of the United States Geological Survey, during flood stages, show silt contents ranging from 12 to 75 per cent of the volumes of the samples. These figures correspond with Dutton's estimates of the silt content of the streams of the Plateau region.[20] He says:

> "It would not be an improbable estimate to say that these spasmodic waters carry nearly three times their own volume of fine material, and it is quite certain that they often carry more than twice their volume."

The San Juan, when it thus carries three times as much silt as water, is literally a river of mud. In fact, the water is always muddy. It is

[20] C. E. Dutton: Tertiary history of the Grand Canyon district. U. S. Geol. Survey Mon. 2, 1882, p. 237.

usually gray to buff in color, but during low stages it assumes a milky color, and during the falling stages of some floods it becomes brick red in color. On one occasion I saw the river run with a smooth, oily movement, like that of molten metal, so red was it and so viscous with silt. At this stage the fish became exhausted and came to the surface, where they feebly swam, with their dorsal fins projecting into the air.

The quantity of silt carried by the river each year, as calculated by the Bureau of Reclamation, is 24,000 acre-feet. At this rate 140 years would be required to transport 1 cubic mile of silt; but the time would be much shorter, because the estimate does not take into account the bed load of sand, pebbles, cobbles, and boulders which slide, roll, and make short skips and leaps; also, the observations by Pierce, who found the river to carry at times from 12 to 75 per cent by volume of silt, indicate that the above estimate does not include all the silt actually carried in suspension.

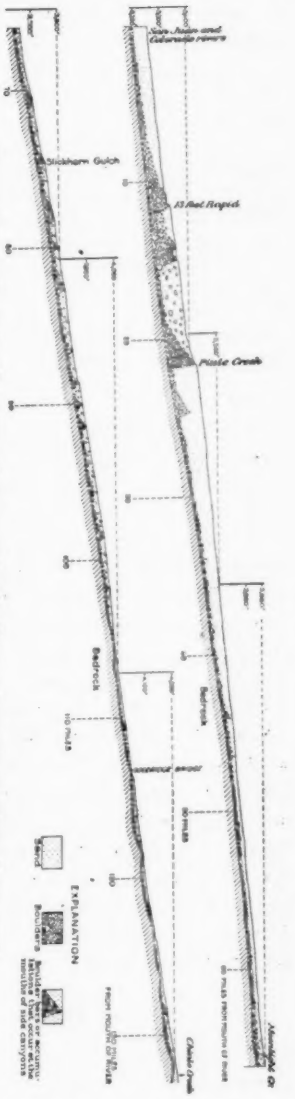

FIGURE 2.—*Profile of San Juan River between Colorado River and Mouth of Chinle Creek, Utah*

Shows possible depth to bedrock and character and inferred distribution of the rock debris under bed of river. Datum is mean sealevel.

A PECULIAR METHOD OF DEBRIS TRANSPORTATION

The San Juan, like other exceptionally swift muddy streams, is characterized by a peculiar method by which the debris is transported. By this method the dunes or hills of debris on the river bed travel upstream. This and other methods of

transportation are described by G. K. Gilbert[21] in the following concise statements:

"Some particles of the bed load slide, many roll, the multitude make short skips or leaps, the process being called saltation. Saltation grades into suspension. . . .

"When the conditions are such that the bed load is small, the bed is molded into hills, called dunes, which travel downstream. Their mode of advance is like that of eolian dunes, the current eroding their upstream faces and depositing the eroded material on the downstream faces. With any progressive change of conditions tending to increase the load, the dunes eventually disappear and the debris surface becomes smooth. The smooth phase is in turn succeeded by a second rhythmic phase, in which a system of hills travel upstream. These are called antidunes, and their movement is accomplished by erosion on the downstream face and deposition on the upstream face. Both rhythms of debris movement are initiated by rhythms of water movement."

The cause of the changes in process has, as pointed out by Gilbert,[22] not been adequately investigated. The dune phase is accompanied by comparatively small downstream-moving waves. The smooth phase has no waves or only small ones. A kind of wave known as sand waves appears when the river passes from the smooth to the antidune phase.

Sand waves are especially well developed during flood stages, when the current is swift and the debris load is heavy. In form they resemble those thrown up by a stern-wheel river steamboat (see plate 9, figure 2). They attain a maximum observed height of 6 or 7 feet and occur as a series of parallel waves at right angles to the channel, though on one occasion they were observed to extend diagonally across the channel. Such a series of waves starts at the downstream end of a swift stretch of water and travels slowly upstream to the head of the stretch. Each wave gradually increases in height and is accompanied at its climax by a breaking toward the upstream side. The process of breaking is known as combing and is accompanied by a roaring noise. Such a noise is continuous during the entire upstream advance of the waves, for some waves are always breaking at the same time. The current is somewhat checked by the waves, but below them it picks up speed and is comparatively free from waves. No sooner has one series of waves died out upstream than a new series appears downstream and begins its upstream advance.

Power and Storage Dams in Canyon

If the proposed storage and power projects on San Juan and Colorado rivers are carried to completion, the mad chase of the San Juan will in

[21] G. K. Gilbert: The transportation of debris by running water. U. S. Geol. Survey Prof. Paper 86, 1914, p. 11.

[22] Op. cit., p. 33.

part be ended, rapids will be silenced, and the region, with its wild beauty, will become accessible to tourists. Then the canyon, with its now turbulent waters, will be partly filled with the placid waters of huge reservoirs; also, the river when it reaches the heads of the reservoirs will change its work from erosion to deposition. An important question concerning the reservoirs is, How soon will they be filled with rock debris? The answer to this question remains for the future, because the data available at present are not sufficient for making an estimate of the total load of debris that is carried each year by the San Juan and discharged into the Colorado.

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VOL. 36, PP. 379-392 JUNE 30, 1925

STRUCTURAL GEOLOGY OF THE MID-CONTINENT REGION: A FIELD FOR RESEARCH[1]

BY SIDNEY POWERS

(*Read before the Society December 30, 1924*)

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INTRODUCTION

Structural geology furnishes a field for research in the Mid-Continent region little appreciated by geologists not working in petroleum. The enormous number of well records, 105,000 in Oklahoma and 35,000 in Kansas, together with samples of formations penetrated, furnish information from which structural details may be studied, both in vertical and horizontal directions, in terms of tens of feet rather than of miles. These records, together with surface structure, mapped in minute detail, supply a greater wealth of detailed geological data than is available in any other area of equal size in the world.

Petroleum geologists engaged in detailed intensive studies seldom find occasion to compile regional data and to deduce conclusions therefrom. The present intensive drilling campaign will ultimately cease and operations will be reduced to the scale now prevailing in the Appalachian oil fields. In the meantime the data now available will be scattered and inaccessible. The time for structural research is the present. Fortunately, the stratigraphic problems have been receiving attention during

[1] Manuscript received by the Secretary of the Society December 31, 1924.

the past year. This paper calls attention briefly to the present status of our structural knowledge, the methods of investigation, and to tentative interpretations.

For the purpose of this discussion, the area considered is restricted to northeastern Oklahoma and southeastern Kansas, but the problems are very similar in central and west-central Texas. The important area in which older rocks are exposed is the Ozark Mountain uplift, which extends from Missouri and Arkansas into northeastern Oklahoma east of Grand River. The southern third of Oklahoma is occupied in part by those portions of the Ouachita, Arbuckle, and Wichita Mountains not concealed beneath overlapping sediments, but the bearing of these mountain uplifts on the problems of northeastern Oklahoma is a separate problem.

Stratigraphy

Stratigraphy in the Mid-Continent region is sufficiently well known, so that several typical illustrations will suffice to demonstrate a thinning of the geologic section over uplifts and a thickening in the intervening depressions, or synclines, when measured from the same formation at the surface. The significant features are the small total thickness of the section and the small individual thicknesses of groups of formations between unconformities, regardless of their widespread distribution. The anticlines shown in the following table include a few of those from which the entire pre-Pennsylvanian section is not eroded, and on them the average thinning over structure is 20 per cent. There is an unconformity or disconformity between the formations of each age except between the Pennsylvanian and Permian.

Thickness of strata, in feet, on and off anticlines, in Oklahoma, from west (Tonkawa) to east (Inola):

	Tonkawa.		Cushing.		Tulsa.	
	On.	Off.	On.	Off.	On.	Off.
Permian	800	950				
Pennsylvanian	3,100	3,250	2,800	3,180	1,600	1,650
Mississippian	0–100	230	0	350	250	275
Devonian-Silurian	0	60	0	50	0–50	75
Ordovician	(300?)	1,200	860	(1,000?)	(300?)	750

	Owasso.		Inola.	
	On.	Off.	On.	Off.
Pennsylvanian	1,200	1,250	500	550
Mississippian	200–250	300–350	275	275–330
Devonian-Silurian	0– 30	0– 50	50	50
Ordovician	0	150+	0	150+

Methods of Study

Surface geology in the Mid-Continent region is mapped with a plane-table, and structure contours are drawn on a scale of 2,000 feet to one inch (1:24,000) or, in greater detail, with a contour interval usually of 10 feet. An accuracy of from 1:8,000 to 1:10,000 is required in instrumental traverses. Areas devoid of traceable outcrops can not be mapped except by drilling and, where subsurface correlations of existing well records are not available, core drilling at shallow depths is used. Excavation of pits to provide outcrops has not proved satisfactory.

Structural geology is based on correct stratigraphic correlation. Correlation in continuous mapping of surface outcrops is by means of lithologic similarity and uniformity of interval. Paleontology of the surface strata is not necessary except where exposures are meager, but there and in subsurface work micropaleontology has given satisfactory results. Chemical analyses of waters, both in shallow and deep wells, have proved that water-bearing horizons each have distinctive chemical characteristics, and that connection between water horizons occurs only along faults or in improperly cased wells.

Subsurface correlations have depended in the past on the reliability of well records, which are made by the driller. The percentage of inaccurate logs is very small. Recently, cuttings from wells have been preserved and studied for microfaunas and heavy minerals with excellent results. More and more of such studies should be fostered and the results published. The few collections of cuttings which are still preserved are in the hands of companies and may be destroyed at any time because of the lack of a permanent custodian.

Structure

Anticlines and folds of anticlinal type, the most common of which is the nose, form the dominant type of structure. In the eastern portion of the area under consideration both anticlines and noses are found at the surface. Farther west, and consequently higher in the stratigraphic section, surface anticlines become very scarce. The Cushing field lies on the largest group of pronounced surface anticlines. Noses increase in number from east to west toward the region of greater cover, as anticlines decrease.

Underground correlations indicate a possible division of surface folds into *reflected* and *surficial* types, the former increasing and the latter decreasing, both in size and height, with depth. The reflected folds increase in steepness downward through the Pennsylvanian, and especially beneath each underlying unconformity. Contrary to the usual condition,

that folding is limited to periods of uplift and erosion, progressive folding or its equivalent effect is noted throughout the section. This can not be explained by shearing or squeezing of beds on folds, because the folds are not sufficiently steep, but it is in part, at least, due to relative condensation of sediments. Surficial folds disappear downward gradually, usually in the Pennsylvanian section.

Most of the folds are small and low. Many can be inclosed within an area one mile square, and the average area inclosed within the lowest closing structure contour does not exceed a square mile. Some of the anticlines, both at the surface and underground, are from two to three miles in length, but the largest folds, such as Cushing, consist of groups of smaller anticlines and domes.

Closure is defined as the amount of structural relief between the highest point and the lowest closing contour on an anticline. The amount in the Pennsylvanian is commonly 5 to 30 feet, sometimes 50 feet or more. Anticlines in the Mississippian, both on the surface and underground, have a greater relief—from 20 to 100 feet or more. Those in the Ordovician beneath the Pennsylvanian have still greater closure—from 30 to 400 feet or more. The amount of closure is frequently proportional to the size of the anticline. It is definitely known that still greater relief occurs on the surface of the underlying basement rocks.

The abundance of anticlinal folds is inversely proportional to size. Most of them are irregularly disposed, without system, both on the surface and underground, but some are aligned and are connected underground by structural saddles to form ridges.

All of the folds are superposed on a homoclinal westerly dip, both at the surface and underground, which varies from 40 to 90 feet to the mile. In the few townships where no noses can be mapped at the surface with existing outcrops, one or more anticlinal folds probably occur in the deeply buried sediments.

Structural History

A description of structural history must commence with the pre-Ordovician basement, on the original configuration of which the overlying structure depends. The basement crystalline rocks are exposed in Missouri, but the topography when the Cambro-Ordovician sediments were deposited must be reconstructed from a study of logs of wells which have penetrated it. This surface was a peneplain of low relief, with small rounded hills, a few sharp, small monadnocks, and some major low ridges of crystalline rocks which may have represented the cores of ancient mountains. The recently uncovered granite hills of the present Wichita Mountains illustrate this type of topography.

Ordovician sediments were deposited with very uniform conditions of sedimentation over a broad area west of Missouri. The folding which accompanied and followed this sedimentation rejuvenated the former hills and made anticlines. Other anticlines besides those which overlie hills were probably formed after sedimentation ceased, but they have not yet been proved by drilling. No anticlines which extend downward into the Ordovician are known to have been formed later; the subsequent periods of folding merely rejuvenated those established at the close of the Ordovician. A few monadnocks may not have been submerged by Ordovician sediments; the record is not clear.

Uplift and erosion followed this, the most important period of folding. The younger Ordovician formations were removed over most of that portion of Oklahoma and Kansas east of Tulsa and Independence.

Formations of Silurian and Devonian ages were again spread over a broad area, but they did not cover all the anticlines which formed topographic hills at this time, and they are thinner on those which they do cover.

After a period of very slight folding and very little erosion, Mississippian formations, including the Chattanooga black shale and the widespread "Mississippi lime," were deposited, but again they were thinnest or absent on the anticlinal hills.

Broad warping, faulting, and minor local structural adjustments and erosion preceded Pennsylvanian deposition. Pennsylvanian sediments ultimately completely submerged the local and regional topographic-structural features, but the positive movement of them persisted either continuously or spasmodically throughout Pennsylvanian and Permian sedimentation. The stratigraphic section over the Ordovician anticlines is everywhere thinned. Some anticlines and many of the undulations in the Pennsylvanian were formed between the reflected folds after Permian sedimentation, but they invariably disappear in depth by thickening—usually thickening of the shale. Some of them extend downward to topographic hills on the top of the "Mississippi lime" and a few disappear in the underlying shales. It is not usually possible to distinguish a reflected from a surficial fold in advance of drilling on the fold itself.

In tracing the history of periodically and perhaps continuously rejuvenated uplifts of small size and of small height, it is natural to inquire, When did these movements cease? They continued in western Kansas until after Cretaceous sedimentation. Folds in the Gulf Coastal Plain in part, at least, reflect buried hills. May not the process of rejuvenated folding in the Mid-Continent area have continued into the Tertiary, in spite of the negative evidence thus far brought forth in studies of the High Plains?

Interpretation of Structure

Degree of folding is proportionate to stratigraphic nearness to the pre-Ordovician basement because of successive rejuvenation of uplift over buried hills. No connection between degree of folding and distance from the Ozark Mountains is apparent east of the Cushing Ridge. Intensity of folding in surface exposure depends on stratigraphic horizon. A structure contour map on the surface of an Ordovician formation would show essentially the same type and size of folds on surface outcrop near the eastern line of Oklahoma as underground 100 miles farther west. There are interruptions of major significance, such as the Granite Ridge (Nemaha Mountains) which extends from northern Nebraska into northern Oklahoma, the Cushing Ridge, and other similar ridges. West and south of Cushing the size of folds increases and the frequency decreases. Possibly the explanation is to be sought in pre-Cambrian folding. The Cushing and Granite ridges seem to have acted as barriers on the west to Ordovician and later folding, which caused the area to the east to be affected as a unit.

This type of folding—small, irregularly distributed, but abundant anticlines periodically rejuvenated—is very different from the Appalachian type of folding with long, parallel anticlines and synclines and from the Rocky Mountain type of broad folding and overthrusting. The term Plains type of folding is introduced for it. The same type may be expected in other broad epeiric basins of gentle yet uniform rate of dip.

No satisfactory explanation for the Plains type of folding has been offered. The Ozark upwarp created the regional west dip and compressed the Pennsylvanian sediments to some extent, but lateral pressure from it, transmitted through the sedimentary section, did not create or rejuvenate the buried hills. Tangential compression, as ordinarily considered in mountain-building, produces other types of structure.

The presence of topographic relief beneath the sedimentary floor is a prerequisite to the formation of buried hills. Successive relative uplifts of this floor, and especially relative elevations of portions of it, are necessary, because the dominant type of folding is the anticline or dome. Relative condensation of sediments has been one of the important factors in accentuating the buried hills, the condensation being most effective in the thick shale sections in which the surficial folds die out. Uniform compression of a large segment of the basement rocks, taking place at considerable depth below the Paleozoic crust, would accentuate buried hills, and this hypothesis is offered as the best explanation for their periodic rejuvenation. Experimental mountain-building simulates compression of a thick prism of sediments and never the compression of a block

of granite whose surface is covered with minute topographic irregularities buried by a thin veneer of sediments, such as exists in the Mid-Continent region.

Isostasy is now considered an important regional factor in mountain-building, but most of the isostacists would hesitate to explain the successive uplift of domes each one mile in diameter and only a few miles apart by isostasy acting locally.

In conclusion, the Plains type of folding presents as complex a problem of origin as do the better-known types. The facts are available and deserve both intensive and extensive study. Only by careful collection and digestion of the data can the problem be solved.

Faulting

A brief epilogue about faulting is added because faulting is one of the conspicuous structural features in the Mid-Continent homocline. Faults are from one mile to three miles in length and are arranged in echelon lines more or less parallel to the strike of the Pennsylvanian, but widely divergent in places from the strike of the underlying rocks. Lines of faulting occur in the Mississippian rocks in eastern Oklahoma, and again in the sandstone ridges in the oil-field region. They have not been found in the important shale belt of outcrop at the base of the Pennsylvanian or in the Permian.

Drilling has shown that the echelon faults are confined to the sandstone section in the middle of the Pennsylvanian of Oklahoma. They seem to disappear upward and downward in shales and also northward in Kansas, where the sandstones are replaced by limestones and shales. It is postulated here that these lines of faulting were formed in relatively brittle sandstones by shearing stresses originating in the post-Pennsylvanian Ozark upwarp and acting against the major buried ridges which formed resistent buttresses.

Other faults are found in pre-Pennsylvanian rocks with trends not parallel to the echelon faults or to the lines along which such faults occur. The deeper faults are of an earlier generation and may be of late Mississippian age.

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DISCUSSION

Mr. K. C. HEALD: Any geologist who is reasonably familiar with structural conditions in the Mid-Continent region will probably heartily indorse Mr. Powers' statement that there is need for research, and that, until observation, compilation of fact, and experiment have confirmed or disproved much that is now speculative, the geologist must often fail in his predictions, not only of the locations of oil or gas pools, but in his conclusions regarding the intensity, the shape, or even the existence of anticlinal structure in the formations that carry oil and gas. This is particularly true where the surface of the earth carries a mantle of alluvium; where absence of stratification, intricate cross-bedding, or tendency to slump makes observations on outcropping rocks untrustworthy, or where the surface rocks represent delta deposits with dips indicative of depositional rather than structural conditions.

Among the questions that plague the geologist, those that touch the relation of surface folding to oil-sand structure are among the foremost. It is true that observation has taught him that the anticlines shown in the outcropping rocks almost never indicate coextensive anticlines in the oil sand, and that folding in the deeper beds is commonly sharper than that in the exposed strata. It is known that the highest point on the anticline in the oil sand rarely exactly underlies the highest point on the surface anticline, and that it may be far to one side or another of the crest of the surface fold. Other equally important relations have been

recognized. However, recognizing a condition in a known field does not necessarily permit predicting conditions in an undiscovered field, unless the facts responsible for the conditions are understood. A logical, believable theory for the origin of the anticlinal folds of the Mid-Continent is therefore a prerequisite for the effective, economic discovery of those folds and for the exploitation of such oil as they may contain.

The theory advanced by Mr. Powers, if I have correctly understood him, is that monadnocks of pre-Cambrian rocks, and of granite in particular, exist below the Paleozoic rocks, that lateral compression has resulted in recurrent uplift of the pre-Cambrian floor, and that the monadnocks have been differentially uplifted, rising farther than the surrounding areas of low relief, and consequently arching or bowing up the overlying sediments of Paleozoic age. This recurrent uplift is indicated by the thinness of the prisms of sediment above the more pronounced folds, such as the Cushing and Ponca City anticlines. Its intermittent nature is shown by some formations having their normal thicknesses over the anticlines, while others are appreciably thinner than elsewhere in the general region.

I quite agree with Mr. Powers that evidence of recurrent uplift is convincing, although I do not know of any evidence that indicates much uplift before the end of Mississippian time. However, there is no apparent reason why there should not have been local movement during Ordovician, Silurian, Devonian, and Mississippian time. Certainly there were tiltings or broad warpings, for the basins of deposition of these rocks were not coextensive and one or more great unconformities is associated with each of these periods in the Mid-Continent region. These same unconformities prohibit a belief that compacting of soft sediments over relief that developed on a pre-Cambrian surface is responsible for folding manifested in the Pennsylvanian rocks that make up much of the surface of the Mid-Continent oil fields, unless the monadnocks were peaks high enough to project above the total thickness of Ordovician, Silurian, Devonian, and Mississippian rocks, and resistant enough to repel the degradational attempts of successive and long-continued periods of erosion. A few such towering monadnocks probably did exist, but the evidence now available indicates that, except for the Nemaha Mountains of Kansas, there was little granite showing above the Mississippian sea, and when that sea receded it must have exposed to erosion an almost featureless expanse. Deformation of this Mississippian surface was not contemporaneous with deposition of the sediments, as some have argued, but followed it. It is true that the surface was arched into domes and anticlines before the deposition of Pennsylvanian sediments, and that the erosion of these domes and anticlines left an abnormally thin Mis-

sissippian section over many folds, for we are reliably informed that the beds that make up these thin Mississippian sections are the lower part of the normal section.[2] It therefore seems probable that when Pennsylvanian sedimentation began the Mississippian surface was one of low relief, on which monadnocks may have represented uplift.

During and after Pennsylvanian time there appears to have been recurrent uplift, and at least in some instances these uplifts were in regions where the pre-Cambrian basement rocks are much closer to the surface than would normally be expected, showing that uplift had also been localized in these regions during the post-Mississippian, pre-Cherokee period of deformation and erosion. That these recurrent uplifts involved the pre-Cambrian basement is apparent. That they are due to lateral stress manifesting itself in the differential uplift of unfaulted monadnocks, as I understand Mr. Powers to maintain, seems impossible. Even if, for the sake of argument, it were admitted that such delicate isostatic adjustments exist that very minute differences in load will ultimately result in readjustment by sinking or by rising, a prism of sediment with a granite hill at its base is slightly heavier than a prism which is identical in every respect except that the siliceous limestone takes the place of the granite, for the weight of a cubic yard of average granite is about 2.66 tons, while that of a cubic yard of average limestone with its pores half full of water is about 2.64 tons.[3] Accordingly, such monadnocks would tend to sink rather than to rise.

Warping, due to reduction in the size of the base of the monadnock, may be what Mr. Powers has in mind. If the simplest possible case be assumed, we would deal with a conical monadnock rising from a featureless plain. If strong lateral pressure resulted in shortening the crust by, say, one-fiftieth, it is at least possible to argue that the diameter of this conical monadnock would be similarly shortened, and that as the volume of the cone remains the same, and the volume equals the base times one-third of the altitude, the tip of the monadnock must have been raised more than the base. However, under even the most favorable conditions imaginable, the shortening will be only of that diameter parallel to the direction of stress, so that the base of the cone will not be diminished in area so much as it will be changed in shape to form an ellipse rather than a circle. Assuming that the inertia of the rocks normal to the direction of thrust prevented elongation of the axis of the ellipse in that direction, the average radius of the ellipse would be decreased by one one-hundredth

[2] F. L. Aurin, G. C. Clark, and E. A. Trager: Notes on the subsurface pre-Pennsylvanian stratigraphy of the north Mid-Continent field. Bull. Am. Assn. Petroleum Geologists, vol. v, no. 2, March-April, 1921.

[3] J. Barrell: The strength of the earth's crust. Jour. of Geology, vol. 22, 1914, p. 219.

rather than by one-fiftieth. This means that in order to get differential uplift of as much as 200 feet, the original monadnock must be about 10,000 feet high, the interior of the monadnock must behave like a plastic body, and the relief must all be upward. This imposes a severe strain on credulity.

Crumpling of the beds due to lateral movement of the monadnocks has been suggested as a possible origin for some of the Mid-Continent folds. The position of the granite bosses below rather than to one side of the anticlines prohibits belief in such an origin for most of the anticlines associated with "buried hills."

It seems to me that Mr. Powers has omitted the first and most important consideration for an understanding of these folds that are associated with "buried hills" of granite, and that any theory which explains the recurrent uplift must also explain satisfactorily the existence and the relations of the granite hills. Persistence of monadnocks on a plain of erosion may explain a few of these granite "highs," but the vagaries of erosion can not explain the existence of a straight-fronted mountain range like the Nemaha Mountains. Such a feature is invariably associated either with folding or with faulting. Furthermore, the approximate parallelism in alignment of the Nemaha Mountain front, the zones of en echelon faults, and the axes of such major anticlines as Cushing, Ponca City, Blackwell, etcetera, is too marked to be passed by as fortuitous. Mr. Powers states that such faults as are known die out both above and below and occur only in the hard rocks. If by this he means they are *manifested* only in the hard rocks, there can be no quarrel with his statement; but few will concede that parallel zones of tear faults 15 to 50 miles long can be due to anything but regional stresses that affected the entire thickness of the stratigraphic column that existed when the faults were made.

A reasonable explanation for the association of buried granite hills and anticlinal folds in Oklahoma and Kansas is that these "buried hills" represent the upthrow sides of faults which cut the granite of the pre-Cambrian floor. Recurrent movement along these faults, whether vertical or obliquely upward, has increased the throw of these faults, resulting in intermittent uplift of the overlying sediments. It naturally follows that the oldest sediments must show the greatest deformation. Those sediments immediately in contact with the granite may also be faulted, but the break in the granite is thought to be for the most part compensated by stretching and bending in the sediments. It is apparent that the steepest side of the anticlines must dip toward the downthrow side of the faults.

It is not believed that all the anticlines of the Mid-Continent lie on fault lines. Such a contention would demand an intricate pattern of closely spaced faults that while theoretically possible seems unlikely. However, lateral movement along parallel faults would of necessity deform the strata in the intervening strip with upwarping or depression in response to localization of stress or incompetency of strata. Compacting of beds over thick lenses of sandstone and over buried relief on surfaces developed during post-Mississippian periods of erosion has also doubtless been a contributing factor.

This discussion applies to those parts of the Mid-Continent field north of the Ouachita-Arbuckle-Wichita line of mountains, which appears to limit the area Mr. Powers had in mind, inasmuch as he states that "folding is of neither the Appalachian nor the Rocky Mountain type."

Mr. SIDNEY POWERS: Replying to Mr. Heald, it is apparent that the brevity of the original paper and the absence of detailed descriptions of structural discoveries within the last two years have obscured the proof of periodic and, possibly, at times, continuous rejuvenation of buried hills irrespective of the *modus operandi* of the process. The dozens of small pools developed in Ordovician horizons and the dozens of small domes which have yielded only gas or water in the Ordovician have furnished sections of which Owasso and Inola are examples. Large oil fields which produce from the Ordovician, including Tonkawa, Thomas, Garber, Blackwell, Depew, etcetera, have confirmed the evidence obtained on the small domes that every Ordovician dome can be classed as a buried hill, and that the major period of folding in northern Oklahoma followed Ordovician sedimentation, and that the folds then developed were more or less irregularly developed east of the Cushing line of folding and were aligned west and south of that line. Furthermore, drilling proves that at least some of these domes overlie higher domes in the underlying granite surface, but not towering monadnocks such as Mr. Heald would deduce from theory. The Nemaha Mountains (Kansas granite ridge) is now known to be a tilted block 300 miles or more in length, from the top of which the younger Ordovician, Devonian, Mississippian, and lowest Pennsylvanian are missing. The buried topographic domes on the block are buried hills reflected in the Ordovician (where present) and in the Pennsylvanian; the ridge itself is the largest buried structural uplift north of the Arbuckle Mountains.

Hypotheses regarding the origin of periodic rejuvenation were enumerated. Whichever may ultimately be accepted, the facts are clear that the individual granite monadnocks, with a length of from one-fourth mile to six miles, and in most instances with an original topographic relief of

less than 100 feet, continued to rise, and that this upwarping was not due wholly to a reduction in size of the base of the monadnock because the folds enlarge downward. Some of the original monadnocks must have had steep sides—the granite hill exposed at Spavinaw, Oklahoma, is about 80 feet wide at the top and slopes off at angles of 20 to 60 degrees; the granite hills of the Wichita Mountains are small, oval knobs.

Faults occur at the surface in two broad zones in Oklahoma, as stated in the original paper. Microscopic study of cuttings of wells drilled on each side of faults exposed at the surface prove that they die out in the Pennsylvanian section. The movement is apparently taken up in the underlying shales by folding or crumpling. Other faults are found underground, and they stop upward in Mississippian or else in basal Pennsylvanian strata. Examples are found at Tonkawa, Cromwell, and Depew. At Tonkawa there are no faults in the Pennsylvanian and the deep-seated fault trends northwest. At Cromwell and Depew the faults at the surface do not overlie the one found by drilling and the older faults trend north-south. The same stresses may have developed both sets of faults and may have been operative over a large portion of Oklahoma. Evidence has yet to be presented that the lines of echelon faulting at the surface are not confined to certain formations rather than to limited zones, and that their exposed geographic limitations are not fortuitous rather than limitary of deep-seated faults.

All pre-Pennsylvanian faults thus far discovered on outcrop in eastern Oklahoma or underground beneath anticlines or domes cut the Ordovician. Mr. Heald postulates a series of faults which cut the granite and which give rise to many of the buried hills. It is strange that faults have not been found on the surface at Spavinaw or on the sides of the Wichita Mountain knobs or underground in the Ordovician, except in a few oil fields, if faulting accounts for buried hills. It is also contrary to Mr. Heald's conception to note that the east dip on the Ordovician in many, if not most, of the small domes of the Tulsa district is less steep than the west or "normal" dip. The few faults which are known in the Ordovician do not offset the structure, and hence do not indicate the type of lateral movement postulated by Fath; they may be interpreted as indicating the breakdown of the domes like the faults on the flanks of Salt Creek and Cat Creek fields in the Rocky Mountain province.

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RELATION OF TEXTURE AND COMPOSITION OF CLAYS[1]

BY FRANK F. GROUT

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INTRODUCTION

The determinations reported in this paper were made with the hope of finding the distribution of common elements and minerals in the fractions obtained by mechanical separation of the several sizes of grains in a series of clays. A little chemical work done in the past few years has been found suggestive and is noted here before reporting the new work.

A composite sample of West Virginia clays was tested by both mechanical and chemical analysis in 1905.[2] The United States Bureau of Soils has made a number of similar determinations on soils,[3] but the

[1] Manuscript received by the Secretary of the Society February 24, 1924.
Accepted for publication by Publication Committee March 24, 1925.

[2] West Virginia Geol. Survey, vol. 3, 1906, pp. 60-62.

[3] See, for example, L. A. Steinkoenig, Distribution of certain constituents in the separates of loam soils. Jour. of Ind. and Eng. Chem., vol. 6, 1914, p. 576.

proportion of silt and clay is small in loams, and the finer sizes were not separated in their work, whereas they are most important in the study of clays.[4] Sven Odén has tested the composition of the fine clay fractions of a Swedish glacial deposit.[5] Widman made a similar test of the fractions from a weathered granite.[6] Schurecht made a microscopic examination of the separates of some American clays, but found no mineral but kaolinite in the finest fraction.[7] The ceramic applications of the data here presented have been discussed elsewhere.[8]

Acknowledgments

Much of the work here reported was done by the writer in connection with the preparation of a report by the Minnesota Geological Survey on the clays and shales of Minnesota.[9] Hearty thanks are due to the Survey for the privilege of using the samples collected through the State. Some of the analyses of "whole clay" were published in that report. Further tests have been made partly by the writer and partly by student chemists, S. F. Darling, Douglas Manuel, and C. W. Sanders, working under a grant from research funds of the Minnesota Graduate School. Grateful acknowledgments are here given for that assistance. Where doubt arose as to any student determination, the writer has run check analyses if material was available, and takes all responsibility for the approximate correctness of the data. The lack of agreement between the whole clay and sum of fractions is not much greater than is to be expected in chemical work by different student chemists.

Description of Samples

The samples for this test were selected from several hundred clays collected by the writer and assistants in several parts of Minnesota. The nature of the deposits is indicated in the tables. They range geologically from pre-Cambrian residual clay through Ordovician and Cretaceous shales to Pleistocene and Recent clays. Chemically, some are rich in iron, some in lime, some in silica, some in alkalies. No effort was made to choose the highest grade clays, though nearly all are serving some

[4] Schurecht found some samples were 98 per cent of the finer sizes called "clay." See Jour. Amer. Ceramic Soc., vol. 3, 1920, pp. 355-378.

[5] One of a series of studies reported in Bull. Geol. Inst. Upsala, vols. 15 and 16, 1916-1919.

[6] R. Widman: Bull. Geol. Inst. Upsala, vol. 8, 1908, p. 184.

[7] H. G. Schurecht: The microscopic examination of mineral constituents of some American clay. Jour. Amer. Ceramic Soc., vol. 5, 1922, pp. 3-24.

[8] Frank F. Grout: Jour. Amer. Ceramic Soc., vol. 7, 1924, pp. 122-141.

[9] Minn. Geol. Survey Bull. 11, 1914. See also U. S. Geol. Survey Bull. 678, 1919. Credit is there given for a few analyses made by assistants.

ceramic purpose. The use of the clay is also given in the tables. Details of the behavior in manufacture and firing are given at greater length in the Survey bulletin.

Preparation of Samples

Twenty-gram samples were shaken in bottles with distilled water to which a few drops of ammonia had been added. Lumpy shales were in certain cases gently rubbed with a rubber-tipped pestle. The disintegrated sludge was then washed through sieves and centrifuged approximately as described in Bulletin 84 of the United States Bureau of Soils. The diameters were checked by microscopic measurement and few grains in any separate varied from the following:

	Millimeter.		Millimeter.
A. Fine clay[10]	0.0	to	.001
B. Coarse clay[10]	.001	to	.005
C. Silt	.005	to	.05
D. Fine sand	.05	to	.5
E. Coarse sand	over .5		

Most of the separations were made by the writer; a few were made by students under his direction. The results in a check test are essentially similar to those obtained by the United States Bureau of Standards.

[10] It is, perhaps, an error to class as "clay" all the grains less than .005 millimeter in diameter, but the term is retained here as the common usage. The error of several methods of estimating "clay substance" in clays was shown in the clay report of the West Virginia Geological Survey, vol. iii, p. 26.

TABLES 1 TO 13

CLAY NUMBER 1.—*Gray Drift, Hutchinson, Minnesota*

Commercially washed to remove pebbles and used for brick and drain tile.

Whole clay.	Fractions.				
	Coarse sand, 17.1 per cent.	Fine sand, 24.7 per cent.	Silt, 38.6 per cent.	Coarse clay, 12.0 per cent.	Fine clay, 7.6 per cent.
Silica.....85.85	53.26	75.72	53.20	46.44	47.0
Alumina..... 7.25	6.48	7.16	8.76	14.82	16.5
Iron oxides..... 4.97	2.54	1.72	3.27	7.52	10.5
Magnesia..... 3.45	5.00	1.76	5.00	3.16	3.0
Lime..... 9.42	14.40	6.56	12.04	8.84	4.5
Soda..... 1.37	1.34	.92	2.14	1.06	.9
Potash..... 1.76	1.66	1.44	2.08	2.38	2.5
Ignition[11]..... 2.10	15.22	1.24	3.29	5.01	9.0
Carbonic acid[11].. 9.10		4.00	8.34	6.85	
Moisture..... 2.10	.32	.06	1.04	3.60	4.6
Titania..... .36	.18	.14	.61	.92	.8
100.73	100.40	100.72	99.77	100.60	99.3

[11] CO_2 estimated on small amounts of material. Where estimated, it is subtracted from total loss on ignition. Analysis of whole clay in U. S. G. S. Bull. 678 has a typographical error.

Sands had visible quartz, orthoclase, dolomite, trap rock, etcetera.
Clays slightly caked and scaly, as if containing colloids.

CLAY NUMBER 2.—*Cretaceous Clay, Clay Bank near Red Wing, Minnesota*

Commercially washed to purify it and used for stoneware

Whole clay.	Fractions.				
	Coarse sand, 1.0 per cent.	Fine sand, 6.5 per cent.	Silt, 49.8 per cent.	Coarse clay, 16.0 per cent.	Fine clay, 26.7 per cent.
Silica.....69.92	37.0	91.28	79.16	53.32	45.85
Alumina.....17.39	1.7	.77	11.59	29.24	32.96
Iron oxides..... 1.68	47.4	5.17	1.68	2.46	2.62
Magnesia..... 1.11	2.0	.73	.97	1.16	1.73
Lime..... .60	1.7	.78	.46	1.32	1.04
Soda..... .07	n. d.	.12	.04	1.04	1.28
Potash..... 2.25	n. d.	.90	1.46	2.48	1.79
Ignition..... 5.45	9.6	.84	3.02	7.32	9.02
Moisture..... 1.10	.9	.00	.08	1.08	3.52
Titania..... .63	n. d.	trace	1.49	1.46	.74
100.20	.....	100.59	99.95	100.88	100.55

Sands had visible limonite (concretionary), quartz, muscovite, and a little black mineral.
Clays formed a crust or scale, as if largely colloidal.

CLAY NUMBER 3.—*Decorah (Ordovician) Shale, Saint Paul, Minnesota*

Used for fancy building blocks and brick and tile.

Whole clay.	Fractions.				
	Coarse sand, .7 per cent.	Fine sand, 1.5 per cent.	Silt, 46.8 per cent.	Coarse clay, 13.2 per cent.	Fine clay, 37.8 per cent.
Silica.....56.35	60.0	61.8	57.20	52.20	50.30
Alumina.....18.63	7.0	10.3	19.78	23.88	22.02
Iron oxides..... 6.19	1.8	3.0	5.20	5.80	6.54
Magnesia..... 2.97	.4	2.3	1.88	2.84	3.32
Lime..... .96	10.9	5.4	1.45	.96	1.05
Soda..... .25	.2	.8	1.34	.70	.68
Potash..... 7.37	4.8	4.9	6.90	6.62	6.70
Ignition..... 4.81	10.8	5.3[12]	2.12[12]	4.90	5.94
Carbon dioxide.. n. d.	large	1.9	1.78	none	none
Moisture..... 2.41	1.5	2.9	1.40	1.80	2.64
Titania..... .65	.2	.5	.72	.92	.78
100.59	97.6	99.1	99.77	100.62	99.97

[12] "Ignition" has been reduced by amount of carbon dioxide determined.

Sands show calcareous fossils, quartz, and limonite.

CLAY NUMBER 4.—*Cretaceous Shale, Springfield, Minnesota*[13]

Used for hollow brick and tile.

Whole clay.	Fractions.				
	Coarse sand, 4.0 per cent.	Fine sand, 16.0 per cent.	Silt, 76.8 per cent.	Coarse clay, 2.1 per cent.	Fine clay, 1.1 per cent.
Silica.....64.08	65.0	62.16	67.84	44.9	33.0
Alumina.....17.48	17.0	16.12	14.54	22.2	18.0
Iron oxides..... 5.03		6.16	4.80	6.3	5.0
Magnesia..... 1.42	1.0	.51	.82	2.6	4.0
Lime..... 1.00	3.0	1.76	.96	4.0	10.0
Soda..... .20	n. d.	1.81(?)	.14	n. d.	n. d.
Potash..... 1.74	n. d.	1.34	1.70	n. d.	n. d.
Ignition..... 7.12	14.0	7.80	6.78	16.0	20.0
Moisture..... 1.00	n. d.	1.40	.56	1.3	6.0
Titania..... 1.19	n. d.	1.07	1.22	1.2	1.0
100.26	.....	100.13	99.36	.....	.....

[13] This is a clay bank on the other side of Springfield from that of which analysis is given in U. S. Geol. Survey Bull. 678, p. 134.

Sands show quartz, black sand, and shale lumps.
Clay contains some carbonaceous matter.

CLAY NUMBER 5.—*Residual Clay from Biotite Schist, Bowlus, Minnesota*

Not used.

	Whole clay.[14]	Fractions.				
		Coarse sand, 18.5 per cent.	Fine sand, 41.7 per cent.	Silt, 38.7 per cent.	Coarse clay, 1.0 per cent.	Fine clay, .1 per cent.
Silica	57.20	36.70	65.12	56.06	40.0	.....
Alumina	18.23	35.41	14.59	21.80	17.0	.....
Ferric oxide	5.45	8.22	4.71	7.41	12.0	.....
Ferrous oxide	5.03	8.14	3.61			.....
Magnesia	1.02	1.89	1.00	1.43	4.0	.....
Lime	.72	.24	.16	.43	5.+	.....
Soda	.61	1.23	.46	.94	n. d.	.....
Potash	.98	1.37	.68	.86	n. d.	.....
Ignition	8.20	6.38	8.58	9.62	18.	.....
Moisture	.24	.00	.36	.92	1.	.....
Titania	1.52	.97	1.21	1.21	1.	.....
	99.20	100.55	100.48	100.68	.....	.....

[14] Modified from that published in U. S. Geol. Survey Bull. 678 to show *Ferrous* iron and corrected amounts of moisture and combined water.

Sands show staurolite, chlorite, and quartz.

CLAY NUMBER 6.—*Red glacial Drift, Coon Creek, Minnesota*

After passing rolls, used for medium vitrified brick.

	Whole clay.	Fractions.				
		Coarse sand, 5.5 per cent.	Fine sand, 5.1 per cent.	Silt, 47.5 per cent.	Coarse clay, 24.6 per cent.	Fine clay, 17.3 per cent.
Silica	60.49	67.57	86.04	64.94	53.06	46.70
Alumina	[15] 14.39	15.53	6.90	12.46	19.85	25.26
Iron oxides	[15] 6.03	4.00	1.28	3.97	5.39	6.34
Magnesia	3.68	2.12	1.23	4.26	5.34	2.56
Lime	3.87	3.34	1.90	3.40	3.28	3.04
Soda	2.17	2.20	.69	2.04	1.10	2.06
Potash	2.53	1.20	1.37	2.43	2.32	1.92
Ignition	5.90	2.40	.82	4.98	7.61	7.72
Moisture	1.94	.34	.02	.42	1.44	3.92
Titania	.42	1.67	.30	1.11	1.08	1.12
	101.42	100.37	100.55	100.01	100.47	100.64

[15] Corrected from the results shown in U. S. Geol. Survey Bull. 678.

Sands show quartz and trap rock.
Clays somewhat scaly, as if colloidal.

CLAY NUMBER 7.—*Glacial laminated Clay from red Drift, Saint Croix River, Pine County, Minnesota*

Not now used.

Whole clay.[16]	Fractions.				
	Coarse sand, trace.	Fine sand, .3 per cent.	Silt, 42.0 per cent.	Coarse clay, 29.7 per cent.	Fine clay, 28.0 per cent.
Silica..... 56.85	.....	76.0	63.38	54.14	47.00
Alumina..... 14.87	.....	13.0	13.45	17.58	18.16
Iron oxides..... 7.40	.....	3.0	4.81	8.14	10.88
Magnesia..... 4.49	.....	1.0	3.46	4.50	5.32
Lime..... 3.58	.....	2.0	4.08	2.44	2.24
Soda..... 1.31	.....	n. d.	1.58	.96	1.22
Potash..... 2.39	.....	n. d.	2.81	2.90	2.88
Ignition..... 6.60	.....	2.5	5.16	7.86	7.08
Moisture..... 1.80	.....	.5	1.14	.34	3.92
Titania..... .55	.....	.5	.54	.68	.92
99.84	.....	.....	100.41	99.54	99.62

[16] Not the same sample as the one reported in Bull. 678, p. 215.

Clay lumps had to be rubbed to break them up. More rubbing might have increased the per cent of fine clay. Clays slightly colloidal.

CLAY NUMBER 8.—*Glacial laminated Clay from gray Drift, North Minneapolis, Minnesota*

Used for cream brick and fireproofing.

Whole clay.	Fractions.				
	Coarse sand, trace.	Fine sand, .5 per cent.	Silt, 79.5 per cent.	Coarse clay, 10.9 per cent.	Fine clay, 9.1 per cent.
Silica..... 50.65	.....	73.2	50.22	44.76	44.66
Alumina..... 10.25	.....	10.3	9.81	14.34	17.21
Iron oxides..... 4.00	.....	.6	3.03	5.08	7.09
Magnesia..... 4.68	.....	2.0	5.77	4.30	2.88
Lime..... 10.65	.....	4.6	12.36	9.88	6.56
Soda..... 1.44	.....	n. d.	1.02	1.30	1.30
Potash..... 1.96	.....	n. d.	1.51	2.15	2.36
Ignition..... 2.10	.....	5.0	1.96	3.92	5.31
Carbon dioxide..12.30	.....		13.60	11.50	7.98
Moisture..... 1.20	.....	.5	.44	2.22	3.76
Titania..... .52	.....	.2	.55	.34	.92
99.75	.....	.....	100.27	99.79	100.03

Sand shows mostly quartz, but a little magnetite, orthoclase, hornblende, calcite, and mica. Clays formed a crust or scale, as if notably colloidal.

CLAY NUMBER 9.—*Loess Clay, Preston, Minnesota*

Used for building brick (and in foundry sands).

	Whole clay.[17]	Fractions.				
		Coarse sand, .1 per cent.	Fine sand, .9 per cent.	Silt, 84.3 per cent.	Coarse clay, 8.5 per cent.	Fine clay, 6.2 per cent.
Silica	70.50	58.	67.7	74.80	51.28	46.48
Alumina	12.28	n. d.	9.5	11.36	19.06	23.86
Iron oxides	4.06	n. d.	5.3	3.10	7.84	7.96
Magnesia	1.81	15. (?)	2.8	1.42	2.47	2.77
Lime	1.27	8. (?)	2.1	1.78	1.82	1.20
Soda	1.73	n. d.	.1	1.39	.61	.58
Potash	1.95	n. d.	3.7	2.22	1.40	1.07
Ignition	3.88	10.	6.9	2.80	10.10	12.00
Moisture	1.92	1.	1.5	.46	4.28	4.18
Titania	.34	n. d.	.5	.68	.92	.32
	99.74	.....	100.1	100.01	99.78	100.42

[17] Not the same sample as the one analyzed in Bull. 678, p. 160.

Sands show quartz, limonite, and mica.
Clays formed scale, as if largely colloidal.

CLAY NUMBER 10.—*Lake Clay, Heron Lake, Minnesota*

Used for hollow brick and drain tile.

	Whole clay.	Fractions.				
		Coarse sand, .4 per cent.	Fine sand, 4.1 per cent.	Silt, 69.4 per cent.	Coarse clay, 16.8 per cent.	Fine clay, 9.3 per cent.
Silica	53.94	60.0	81.4	56.28	42.42	42.46
Alumina	11.39	19.0	7.0	10.80	14.55	19.93
Iron oxides	3.29		1.0	2.24	6.11	10.22
Magnesia	3.47	8.0	.8	3.77	2.71	2.90
Lime	9.80	4.0	4.5	10.22	12.22	4.87
Soda	2.34	n. d.	n. d.	1.46	1.73	1.45
Potash	.76	n. d.	n. d.	1.35	.99	.92
Ignition[18]	4.16	4.0	2.1	3.00	5.58	9.32
Carbon dioxide	8.62	n. d.	n. d.	9.38	10.68	2.42
Moisture	1.64	2.	.3	.90	2.72	5.28
Titania	.65	n. d.	.2	1.00	.84	.65
	100.06	.....	.....	100.40	100.55	100.42

[18] Carbon dioxide, where estimated, is subtracted from total loss or ignition.

Sands show mostly quartz, with traces of limonite.
Clays formed scale, as if largely colloidal.

CLAY NUMBER 11.—*Swamp Clay, Tower, Minnesota*

Used without much success for building brick.

Whole clay.	Fractions.				
	Coarse sand, 4.0 per cent.	Fine sand, 18.1 per cent.	Silt, 73.3 per cent.	Coarse clay, 3.1 per cent.	Fine clay, 1.5 per cent.
Silica..... 52.92	58.78	48.92	50.52	43.4	1.0
Alumina.....[19] 16.73	16.00	18.16	16.88	19.1	1.0
Iron oxides...[19] 4.98	4.16	4.90	4.93	8.1	n. d.
Magnesia..... 3.78	2.96	3.68	6.73	7.0	5.0
Lime..... 5.95	4.95	6.64	5.88	5.7	25.0
Soda..... .97	2.42	.70	1.45	n. d.	n. d.
Potash..... 2.32	2.89	3.36	2.90	n. d.	n. d.
Ignition..... 8.85	6.75	11.60	8.40	11.1	22.0
Moisture..... 3.33	1.12	2.10	2.06	.4	.....
Titania..... .52	.52	.56	.61	.7	n. d.
Sulphuric oxide.....	.....	.....	.....	.....	44.0
100.35	100.55	100.62	100.36	.....	.....

[19] Corrected from the results shown in U. S. Geol. Survey, Bull. 678.

Coarser sizes are clay lumps not broken by a rubber pestle.
The "fine clay" is mostly soluble salts, gypsum.

CLAY NUMBER 12.—*River Clay as recently deposited by the Minnesota River at Le Sueur, Minnesota*

Used for red brick.

Whole clay.	Fractions.				
	Coarse sand, 4.1 per cent.	Fine sand, 25.7 per cent.	Silt, 58.5 per cent.	Coarse clay, 6.0 per cent.	Fine clay, 5.5 per cent.
Silica..... 62.20	52.0	64.50	61.60	50.90	42.24
Alumina..... 7.77	9.0	8.12	8.33	14.31	13.82
Iron oxides..... 4.53	5.3	4.15	2.89	8.19	7.03
Magnesia..... 3.18	3.5	2.06	4.23	2.69	1.66
Lime..... 7.21	8.8	7.40	8.30	4.10	9.10
Soda..... 3.58	2.4	2.10	2.27	2.02	1.22
Potash..... 1.63	1.1	2.12	1.73	1.90	3.42
Ignition..... 9.27	13.7	8.30	11.52	11.78	15.82
Moisture..... 2.15	2.9	.30	.20	3.96	4.90
Titania..... .41	.6	.37	.50	.60	.69
101.93	100.1	99.42	101.57	100.45	99.90

Sands show fragments of wood, shells, quartz, and lumps of shale and other rocks.
Clay seems oily rather than colloidal.

TABLE 13.—*Summary Table of the Relation of Texture to Composition in Twelve Minnesota Clays*

		Coarse sands.	Fine sands.	Silts.	Coarse clay.	Fine clay.
Silica	Average	54.83	71.15	61.29	48.07	40.61
	Maximum	67.57	91.28	79.16	54.14	50.30
	Minimum	36.70	48.92	50.22	40.00	[20] 1.00
Alumina	Average	13.02	10.16	13.30	18.83	18.97
	Maximum	35.41	18.16	21.80	29.24	32.96
	Minimum	1.7	.77	8.33	14.31	[20] 1.00
Iron oxides	Average	11.65	3.72	3.94	6.91	7.42
	Maximum	47.4	8.32	7.41	12.00	10.88
	Minimum	1.8	.60	1.68	2.46	2.62
Magnesia	Average	4.19	1.66	3.31	3.56	3.19
	Maximum	15.00	3.68	6.73	7.00	5.32
	Minimum	.40	.51	.82	1.16	1.66
Lime	Average	5.93	3.65	5.11	4.96	6.24
	Maximum	14.40	7.40	12.36	12.22	[20] 25.00
	Minimum	.24	.16	.43	.96	1.04
Soda	Average	1.63	.86	1.32	1.17	1.19
	Maximum	2.42	2.10	2.27	2.02	2.06
	Minimum	.20	.10	.04	.61	.58
Potash	Average	2.17	2.20	2.33	2.57	2.62
	Maximum	4.80	4.90	6.90	6.62	6.70
	Minimum	1.10+	.68	.86	.99	.92
Ignition	Average	8.62	5.08	7.05	10.91	12.51
	Maximum	14.00	11.60	15.56	18.00	12.00
	Minimum	2.40	.82	2.12	4.90	5.94
Titania	Average	.69	.50	.85	.89	.79
	Maximum	1.67	1.21	1.49	1.46	1.12
	Minimum	.18	trace	.50	.34	.32

[20] Soluble salts.

DISTRIBUTION OF ELEMENTS BY SIZES OF GRAIN

The prevailing ideas on the subject of the concentration of certain elements in certain sizes of grain have been developed from scant data. Steinkoenig's data for soils[21] and the conclusions from West Virginia tests[22] can now be somewhat corrected.

Silica is the most abundant oxide in all cases (except the rare "fine clay" with more soluble salt than sediment). The silica averages show clearly, as nearly all the individual samples do, that silica tends to concentrate in the fine sand (.05 to .5 millimeter). Coarser particles usually represent unaltered rock fragments with many minerals or concretions of minerals other than quartz.

Alumina and iron oxides increase from sand to the finest sizes. The high iron content of coarse sand in the Minnesota average is largely a consequence of a single sample in which limonite concretions are abun-

[21] Op. cit., p. 576.
[22] Frank H. Grout: Op. cit., pp. 60-62.

dant. They are coarse enough to be washed out in preparing the clay for use commercially. Nevertheless, the tendency for iron to be high, both in the coarsest and finest fractions, is shown by the results of all the work.

Potash averages show a clear tendency to be at a maximum in the finer sizes, and most individual samples agree. Exceptions result from occasional coarse feldspars.

Phosphorus is reported by Steinkoenig to be largest in the finest sizes.

Combined water is found in maximum amounts in the fine clays and is abundant in sands only when limonite or shale lumps appear in those fractions.

Lime, magnesia, soda, and titanium vary erratically. Lime, as fossils and concretions, tends to remain with the coarser fractions, but as me-

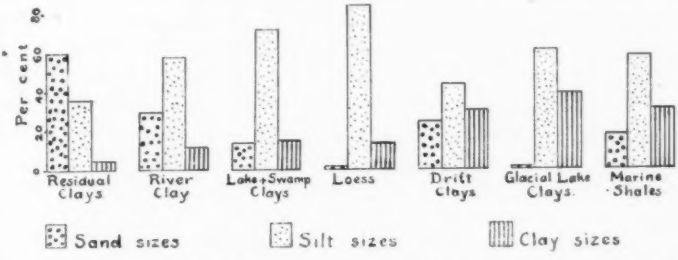

FIGURE 1.—*Diagrams of the Variation in per cent of the several Constituents, with the Size of Grain in Twelve Minnesota Clays*

chanical sediment it is commonly as fine as silt and may be abundant in the clay sizes. Magnesia in dolomite may behave similarly, but as a silicate, more or less hydrous, its behavior is erratic. It shows a slight tendency to be more abundant in the finer sizes. Soda seems wholly erratic in its behavior, though part of the trouble may be traced to inaccuracy and incompleteness in the chemical work. Titanium is well distributed in all the separates.

There are two types of clay that do not follow closely the general trends indicated by the averages, namely, residual clays in which the coarse original minerals may contain elements commonly concentrated in the fine fractions, and clays in which concretionary action has made coarse lumps out of some soluble constituents that commonly occur in fine clays. If these two exceptions are omitted, there is a more uniform tendency for all clays to fall into simple series—silica at a maximum in fine sands; alumina, iron oxides, potash, and to some extent magnesia, showing larger amounts in the finer sizes.

Mineral Development of Clays

Clays being derived from other rocks, either by weathering or by transportation and deposition of the products of weathering, have many accidental minerals, depending on the original rock and the processes involved in their deposition.

Merrill and Clarke have given good summaries of the mineral changes and tendencies of rock weathering.[23] The most notable tendencies are the concentration of alumina and ferric oxide in the residue. It is noteworthy that these broad compilations show a concentration not only of kaolinite, but also of iron minerals (important fluxing impurities of clays). Many examples of the concentration of ferric oxides by leaching are cited in connection with studies of iron ore.

In certain cases other minerals must be similarly concentrated, and special conditions may vary so widely as to alter the product notably. For example, manganese, if present, must commonly behave as iron does.[24] In the presence of vegetable acids, even iron may be rapidly leached after the alkaline earths have been removed.[25] It is thus clearly evident that the minerals depend on a variety of conditions. No list can be set up as a standard of much value.

The minerals actually found in clay are listed by Merrill[26] and by Ries.[27] Over 50 minerals have been identified, mostly in the coarser portions constituting the sand or silt fractions of the clay. The mineral nature of high-grade clays is probably simpler and can be fairly estimated from microscopic examination, as was done by Somers,[28] who notes the relative amounts of 12 minerals. In the more abundant, more impure clays of the larger geologic formations, however, no satisfactory method has been devised for the study of the finest fractions—grains below .001 millimeter. Microscopic study of such grains is not conclusive in most cases,[29] and the minerals have been, and probably must be, estimated

[23] G. P. Merrill: Rocks, rock weathering, and soils. The Macmillan Co., 1913. See page 193.

F. W. Clarke: Data of geochemistry. U. S. Geol. Survey Bull. 695, 1920, pp. 482, 483, 484, 487, 489.

[24] R. A. F. Penrose: Manganese. Ann. Rept. Geol. Survey of Arkansas for 1890, vol. 1.

[25] J. W. Gruner: Origin of sedimentary iron formations. Econ. Geol., vol. 17, 1922, p. 430.

See, also, F. Weiss: Vorkommen und Entstehung der Kaolinerden. Zeit. prakt. Geol., 1910, p. 365.

[26] Op. cit.

[27] H. Ries: Clays, their occurrences, properties, and uses. Wiley and Sons, 1906, pp. 40-93.

[28] R. E. Somers: Microscopic study of clay. U. S. Geol. Survey Bull. 708, 1922, pp. 292-303.

[29] In one case where the finer fractions from elutriation were studied they were reported wholly as "kaolinite and colloid." See H. G. Schurecht, Jour. Amer. Ceramic Soc., vol. 5, 1922, pp. 3-24.

from the analyses and a study of the coarser fractions. An attempt is here made to find the best basis for such estimates.

Minerals in fine Clay

Former suggestions

Some few fine clays have so nearly the composition of kaolinite that it is commonly assumed to be present. Most good kaolins, however, are coarser than the "clay fractions" in a mechanical analysis, and a large number of fine clays have not the composition of kaolinite; so that the assumption that kaolinite is present in fine clays is not entirely safe. The certainty of some variation in the clay substance is shown by the work of Brown and Montgomery.[30]

Estimates of the other minerals have been made by several students of clays. Aluminous hydrate, either crystalline or colloidal, may be expected.[31] Van Hise suggests that some of the water is combined in hydrous minerals such as zeolites.[32] Hutchings found that while feldspar and biotite, chlorite, and clastic muscovite were absent from the fine parts of Carboniferous shales, a new micaceous mineral could be detected.[33] Mansfield found glauconite in the finest fractions from greensand.[34] Sven Odén showed that in a glacial clay the portion soluble in hydrochloric acid was probably less than 30 per cent of the fraction here called "coarse clay," but over 90 per cent of the finest portion he separated.[35]

Some negative evidence also may be of value. Merrill notes that epidote and quartz and magnesia minerals (mica shreds) must be mostly too coarse to pass a 120-mesh sieve.[36] Clarke says that quartz is the principal mineral in sands, while in river silts hydroxides and hydrous silicates predominate; also, that the shales have no distinctive minerals, except that iron is more largely ferrous than in clays.[37]

Microscopic study has led others to still other assumptions, but the grains in question are so small that microscopic identification can hardly be accurate. There seems to be no suggestion in the literature of evidence of the existence of fine-grained minerals of soda, magnesia, etcet-

[30] G. H. Brown and E. T. Montgomery: Dehydration of clays. U. S. Bureau of Standards Technologic Paper 21, 1913, p. 12.

[31] M. G. Edwards: Aluminum hydrates in clay. Econ. Geol., vol. 9, 1914, p. 112. H. Stremme: Centr. Min., 1911, pp. 205-211.

[32] C. R. Van Hise: Treatise on metamorphism. U. S. Geol. Survey Mon. 47, p. 893.

[33] W. M. Hutchings: Clays, shales, and slates. Geol. Magazine, vol. 33, 1896, p. 310.

[34] G. R. Mansfield: Character of New Jersey greensand. Econ. Geol., vol. 15, 1920, p. 554.

[35] Bull. Geol. Inst. Upsala, vol. 16, 1919, p. 148.

[36] Op. cit., pp. 191-192.

[37] Op. cit., pp. 499-500 and 543-545.

era, except the presence of the elements in analyses and the minerals found in the coarser fractions. The data of this paper are the basis of a further discussion of minerals below.

ESTIMATES BASED ON KNOWN EFFECTS OF WEATHERING

The minerals developed by weathering are finer grained than the average rock from which they have formed. The minerals of a clay are, furthermore, subject to alteration by weathering almost in proportion as they are fine grained, and expose greater surfaces to chemical attack. Everything thus points to the occurrence of the common products of weathering in the finest clay.

The known list of minerals, however, resulting from weathering is so long as to leave much doubt of the actual combination present. Iron, for example, may develop in clays as limonite, siderite, hematite, the less known nontronite, or as some other hydrous silicate. Leith and Mead, in summarizing the trend of opinion up to 1915, say that shales may have chlorite, serpentine, and talc, but are more likely to contain oxides, carbonates, and hydrates; also, that potash may be present as sericite, and adsorbed or combined with the finer or colloidal material.[38] Quartz, which is normally increased by weathering, certainly can not be assumed to increase in the finer fractions of a clay.

ESTIMATES BASED ON COARSER FRACTIONS

The progressive mineral changes from sand to clay sizes seem to be dominated, first, by a disappearance of the residual or glacial pebbles of large size, and in the fine sand an increase in the amount of quartz; second, by a steady decrease in quartz from silt to the finest clay. As quartz decreases, other minerals are commonly assumed to remain fairly constant or to increase. Some error may be involved in this assumption, for Hutchings reports that feldspar, for example, does not persist in the finer sizes, though present in the silt. Some ferric iron mineral also certainly increases. The whole method is only a rather unreliable assumption, but may be used if no better scheme is discoverable.

The Calculation of Minerals from Analyses

It has been stated that clays of notable commercial value have practically negligible amounts of minerals other than kaolinite, quartz, feldspar, and mica, and that we may well calculate these minerals from the

[38] C. K. Leith and W. J. Mead: Metamorphic geology. Henry Holt, 1915, pp. 77, 78, and 88.

complete analyses.[39] The clays here tested, while not all of large commercial value, are largely used and certainly present a more complex list of important minerals.

Leith and Mead have presented an estimate of the mineral composition of average shale based on a calculation from an average analysis.[40] (See Table 16 for the minerals they assume to be present.)

Purdy has made some calculations based on the analyses of fine clay in an attempt to determine whether kaolinite is actually present in it.[41] He notes, as Merrill has,[42] that the method of mechanical analysis by which fine clays are separated for chemical tests leaves with the finest fraction nearly all the soluble salts and the potash or other salts adsorbed by colloids. (See clay number 11 in this work as an extreme case, in which gypsum constituted most of that fraction.)

Still other results have been obtained showing a further difficulty in any attempt to calculate these minerals. The fine clays with particles less than .001 millimeter in diameter have no doubt some particles so fine that they are no longer properly minerals, but colloidal solutions or gels, with a variety of adsorbed salts. The United States Bureau of Soils have a fairly conclusive demonstration that soils contain inorganic as well as organic colloids, such as have long been suspected in clays. These have been isolated and appear to be essentially silicates of iron and aluminum; the small amounts of lime, magnesia, potash, and soda may or may not be parts of the colloid.[43]

With so many disturbing factors, it may be doubted whether a satisfactory mineral diagnosis can be made of the finest clays. While the chemical data may be fairly accurate determinations, the minerals are only rough estimates, but the abundance of fine clays in some deposits makes it desirable to assemble what information is available and make the best estimate possible.

Attempted Calculation of Minnesota Clay Minerals

An attempt has been made to estimate roughly the mineral content of the silt, coarse and fine clay fractions of each of the samples studied. The guiding principles in making such an estimate are admittedly open to criticism and revision, but are here summarized:

[39] H. S. Washington: The calculation of the "rational analysis" of clays. Jour. Am. Ceramic Soc., vol. 1, 1918, pp. 405-421.

[40] Leith and Mead: Op. cit., p. 76.

[41] R. C. Purdy: Qualities of clays suitable for making paving bricks. Illinois Geol. Survey Bull. 9, 1908, pp. 182-185.

[42] Op. cit., pp. 121 and 365.

[43] Milton Whitney: Fundamental principles established by recent soil investigations. Science, vol. 54, 1921, p. 350.

1. *Titanium oxide* may be leucoxene (titanite) or rutile; the common alteration product of titanium minerals is leucoxene, while rutile appears more commonly in slates than in clays. Xanthitane, a hydrous aluminum titanite, might be expected also.

2. *Potash* is calculated to muscovite and orthoclase, part to each (though part of it may be adsorbed and not really in mineral combination). Galpin suggests a gradation from sericite through hydromica to kaolinite,[44] but the composition of hydromica is so variable that the calculation of minerals is best confined to the end members of the series. The certainty of at least two states of combination is shown by Parr and by Schmitt.[45] Possibly zeolite would be a more reasonable assumption than feldspar, since Hutchings reports definitely that feldspar disappears as grains grow fine; but the amounts of combined water and the presence of feldspar in coarser sizes are taken as evidence enough of a little feldspar in the fine clay, as has been commonly assumed.

3. *Soda* is calculated (by analogy with potash) to feldspar and paragonite (a sodium mica).

4. *Lime* is commonly in the carbonate, calcite, or dolomite. Feldspar and other calcium silicates are not to be expected. If there is too little carbonic acid and too much combined water, zeolite is more probably present. Many cases arise in attempts at calculation where some hydrous mineral must be assumed to contain lime as well as alkalies, even though none have been recognized in the coarser fractions.

5. *Magnesia* is in dolomite in a few clays, but evidently in a hydrous silicate in others, whether chlorite, talc, serpentine, or a biotitic equivalent of the sericite commonly reported. Probably, as Washington suggests, there is little error in considering it serpentine, for the minerals are not very different in composition and they are rarely present in large amounts.

6. *Iron oxide* is hematite in some red clays and limonite in some brown ones. (Nontronite may occur, but has not been calculated.) In the black clays and the lighter green and gray ones the state of combination is more uncertain. In some there may be carbonate; the black shales may have sulphide and the green ones chlorite, or glauconite. In all shales, as distinct from surface clays, it is preferable to calculate the iron

[44] S. L. Galpin: Studies of flint clays and their associates. Trans. Amer. Ceramic Soc., vol. 14, 1912, pp. 306 and 338.

[45] About two-thirds of the potash of shale is more soluble than the rest. See S. W. Parr and M. M. Austin: Potash shales of Illinois. Jour. Ind. and Eng. Chem., vol. 13, pp. 1144-1146.

H. A. Schmitt: Possible potash production from Minnesota shale. Econ. Geol., vol. 19, 1924, pp. 78-79.

as dominantly in ferrous minerals; for, even if the determination is inaccurate, analyses show that shales are reduced by organic matter.[46]

7. *Combined water* is first assigned to the foregoing, and then the remaining water and alumina are used in calculating kaolinite (or rarely some other "clay mineral").

8. *Silica* is first assigned to the silicates of the preceding paragraphs, and in nearly all cases some will be left to form quartz.

9. *Special cases* arise commonly. An excess or deficiency in some constituent usually furnishes a guide for readjustments. The possible cases are too numerous for further detail here.

[46] F. W. Clarke: Op. cit., p. 545.

TABLE 15.—*Calculated Minerals of the Twelve Minnesota Clays analyzed, in per cents of the separated Fractions*

	1			2			3			4			5			6			7			8			9			10			11			12		
	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.	Silt.	Coarse clay.	Fine clay.
Kaolinite and other clay minerals	3	13	13	14	40	52	0	4	5	19	21		37			0	15	25	2	7	6	5	13	19	0	32	47	10	22	31	0	10		0	9	11
Sericite and paragonite	0	20	21	12	30	27	39	38	37	14	17		7			21	20	16	24	27	30	13	18	20	27	18	14	12	11	8	15	11		15	24	26
Quartz	23	22	23	66	16	4	21	13	9	48	14		25			37	19	8	38	25	15	34	22	19	56	25	15	35	16	10	13	12		45	29	17
Limonite, hematite (and pyrite)	3	9	12	2	3	3	5	0	0	0	[47]3		4			4	5	7	5	9	12	[48]3	6	8	4	9	9	3	7	12	0	0		3	10	8
Calcite and dolomite	19	15	8	0	0	0	4	0	0	0	3		0			4	0	0	5	0	0	29	25	16	3	2	2	21	24	6	3	0		23	13	20
Serpentine and chlorite	12	7	7	3	3	4	2	21	23	11	15		14			10	12	6	7	10	12	5	2	0	3	6	7	5	4	7	23	31		0	0	0
Feldspars	30	9	9	1	2	2	25	19	19	1	0		8			17	9	8	13	7	5	9	10	8	5	1	0	12	12	12	19	0		14	8	3
Zeolites	6	0	0	0	2	3	0	2	3	0	17		0			4	15	23	5	12	12	0	1	5	0	0	0	0	1	9	24	32		0	0	8
Titanite and rutile	1	1	1	2	3	2	2	2	2	3	3		2			3	3	3	1	2	2	1	1	2	2	2	1	2	2	2	1	2		1	1	2
Carbonaceous matter	0	0	0	0	0	0	0	0	1	2	5		0			0	0	0	0	1	1	0	0	0	0	2	2	0	0	0	0	0		0	2	2
Water	1	4	5	0	1	3	1	2	3	1	1		3			0	1	4	1	1	4	1	2	4	1	4	4	1	3	5	2	1		1	4	5
																																Mainly soluble; gypsum			

[47]Partly pyrite. [48]Magnetite.

SUMMARY TABLE 16.—*Comparison of the calculated Minerals of the Averages of finer Fractions from mechanical Analyses of Twelve Minnesota Clays*

	Silt.	Coarse clay.	Fine clay.	Average shale, estimated by Leith and Mead.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
Kaolinite and clay minerals	7.5	17.0	23.2	10
Sericite and paragonite	16.6	21.2	22.1	18
Quartz	36.7	19.3	13.1	32
Chlorite and serpentine	8.2	10.3	7.3	6
Limonite, hematite (and pyrite)	3.0	5.5	8.0	5
Calcite and dolomite	10.5	7.5	5.7	8
Feldspars	12.6	7.2	7.3	18
Zeolites	3.0	7.5	6.9+	..
Titanite and rutile	1.7	2.0	1.7	1
Carbonaceous matter	.2	.9	.6	1
Moisture	.9	1.3	4.1	..

While these tables show the wide variation in the several samples, the trend is in most cases much the same as in the average, namely, kaolinite and limonite are larger and quartz and carbonates smaller as the grain is finer; others are less regular.

The whole clays used in this study have an average composition close to average shale, but the fine clay differs a little from either average, having more kaolinite, zeolite, and limonite, but less quartz, carbonate, and feldspar.

THE AMOUNT OF KAOLINITE IN CLAY

Based on such assumptions, the calculated kaolinite in the "clay fractions" of twelve Minnesota clays averages about 20 per cent, ranging from 4 per cent to 53 per cent. It would probably be useless to suggest that any ordinary clay had *no* kaolinite. Purdy has calculated that all grades of sizes of clay have kaolinite,[49] and in this he is probably right. Some very plastic samples, however, have much less than 10 per cent of kaolinite by calculation.

Thus, if shale number 3 has potash in mineral combination its content of kaolinite must be very small—around five per cent. In several cases the calculated kaolinite is almost doubled if most of the potash is considered adsorbed instead of combined; but it is, perhaps, most probable that only a part of the potash is adsorbed, and at least in the shales it is held so firmly that it is more likely in the form of sericite.

Again, clay number 7 is so plastic and has so little kaolinite that one is tempted to suggest the presence of nontronite, the ferric kaolinite, instead of iron oxides, to explain its plasticity.

[49] Purdy: Op. cit., pp. 203-204.

Finally, whether these assumptions are approved or not, the data indicate what has occasionally been noted before, that clay should not be defined so as to give an impression that it is over half kaolinite. Clay is not dominantly or essentially kaolinite in that sense.

Petrographic Applications

Estimating the nature of clay formations

A petrographer in estimating the minerals of clay may be guided by a variety of evidences. In the absence of all data on a specific clay, the composition of the average, as calculated to minerals by Leith and Mead, is our only recourse. In most cases three points serve to modify the average considerably: (1) The field occurrence, (2) the physical character of the sample, and (3) the visible coarser minerals.

1. The field occurrence helps only a little in estimating the mineral characters. The sandy portions in clays of different origin certainly differ, but differ erratically, especially in the residual and glacial deposits. Clarke[50] gives the following general notes: River silts have more hydroxides and hydrous silicates than the sands; residual clays are much leached of metals except alumina and iron; glacial clays and loess are much more likely to have lime and alkali minerals; shales have more ferrous than ferric minerals.

An inspection of Table 15, with attention to the origin of the several samples, reveals a few additional noteworthy tendencies, but the statement of them is based on such scant data that it must be very general, and it is subject to correction by further work.

Marine shales seem to have more sericite and more hydrous ferromagnesian silicate and possibly more feldspar than other sedimentary clays.

River clays have more quartz and carbonate, but less kaolinite and less hydrous magnesian silicate, than other clays.

Clays originating in glacial or other lakes and swamps and wind-blown loess are less definitely characterized and in most cases intermediate between river clays and marine shales.

2. Physical characters include color, grittiness, and fusibility. A test for effervescence is more chemical than physical. Plasticity is not a reliable guide to any mineral; clay number 3 is more plastic than either numbers 1, 9, or 12, which have more kaolinite. In this case it seems likely that clay number 3 is more plastic because of its higher proportion of the "clay fractions," even if those fractions are not kaolinite. Possibly they are more colloidal.

[50] Op. cit., pp. 499-510.

The black colors indicate organic matter and pyrite; green suggests chlorite and serpentine; red indicates hematite; and yellow or brown, limonite. A white or gray clay, if refractory, has high kaolinite or quartz.

3. Finally, it is suggestive to study the coarser sizes by washing out the finer with more or less care and identifying the coarser minerals either physically or optically. In connection with any minerals so found, allowance should be made for the tendency to variation with texture, shown in the tables above.

This general outline of petrographic method must still be subject to modification. Close observation is needed to avoid errors. No account is taken of organic or chemical precipitates which may contaminate a deposit, but such cases can usually be detected by the geologist. Illustrations may be selected from the clays studied in this paper. Clays numbers 1, 6, 8, and 12, with lime and iron minerals persisting through the sands and silt, may reasonably be expected to have the same in the fine clay. On the contrary, clay number 3, with calcareous fossils, may be expected to have much less lime in the fine clay, and clay number 2, with iron in visible concretions, may similarly be expected to show less iron in the finer portions.

ESTIMATING THE ORIGIN OF CLAY FORMATIONS

This petrographic problem is almost the converse of the foregoing. In the absence of fossils and conclusive field evidence, some estimate of the origin of a clay may be made from (1) minerals, (2) textures, or (3) analyses.

(1) The minerals of a sample are those seen in the coarser fractions (or calculated from analyses). The coarser minerals are abundant and varied in residual and glacial clays. The minerals visible in clays numbers 1, 6, and 8 of this study are at once suggestive of glacial origin, and the marine fossils of shale number 3 are definite evidence of origin. The minerals calculated from analyses can hardly be of any more value than the analyses themselves.

(2) The textural characters of some 14 Minnesota clays, classified as to their origin, are shown in the diagram, figure 2. While the differences may be more or less characteristic, the data are too scanty to be broadly applied. Only one river clay and one sample of loess are included. Not more than three samples are averaged for any of the diagrams. It should be noted, furthermore, that the results are not based on a study of mechanical sediments in general, but are limited to deposits classified as clay, mostly commercial, and partly of residual origin rather than sedimentary. Several features of the diagram, however, are noteworthy.

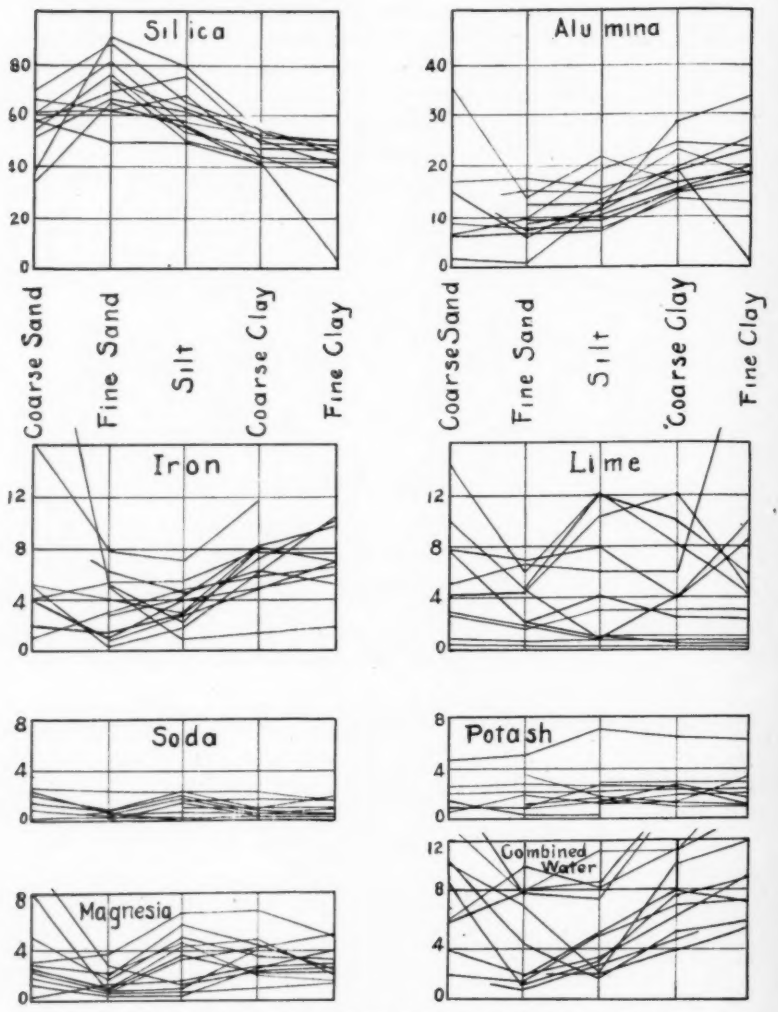

FIGURE 2.—*Textures of several geologic Types of Clays in Minnesota*

Note that the data refer mostly to commercial clays; not to sediments in general.

The clay substance (grains less than .005 millimeter in diameter) constitutes a surprisingly small proportion of the clays in natural occurrences. Silt is the most abundant fraction in all except the residual clays; this is even more notable when the clays and sands are divided as in actual mechanical analyses. The wind-blown loess is particularly well sorted, practically all the grains being of the silt size.[51]

(3) The differences in composition of clays of different origin are reported by Clarke,[52] but it is likely that analyses are too laborious to be commonly used to determine origin. It is very unlikely that a combined mechanical and chemical analysis would be made to see if the distribution of elements by sizes of grain was that characteristic of a clay of known origin. The tables in this paper, however, indicate some relation between that distribution and origin.

Summary

Twelve Minnesota clays have been separated mechanically into fractions of different grain size. These have been analyzed.

Silica is at a maximum in the fine sands of most clays. Alumina and iron oxides and potash, with a minimum in fine sands, are at their highest in fine clays. Other oxides show less regularity.

An attempt has been made to improve the estimates of mineral composition of the finest particles, but probably these estimates will always be somewhat unsatisfactory, because colloidal and adsorbed matters have not the definite composition of any mineral; nevertheless, the minerals can generally be closely estimated. Kaolinite and a ferric mineral are notably more abundant in the finer sizes; quartz and carbonates are less abundant; others vary erratically. Zeolites are more probable than feldspars, especially the lime feldspars. In some commercial clays the amount of kaolinite may be very small.

Petrographically, the work makes possible a more accurate estimate of minerals in clays and a correlation of texture and minerals with origin.

[51] Compare the conclusions of M. I. Goldman: The petrography and genesis of sediments. Maryland Geological Survey, 1916.

[52] Op. cit., pp. 499-500.

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GLACIAL KANKAKEE TORRENT IN NORTHEASTERN ILLINOIS[1]

BY GEORGE E. EKBLAW AND L. F. ATHY

(*Read before the Society December 30, 1924*)

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INTRODUCTION

Widespread deposits of sand and rubble extend throughout the entire valley of Kankakee River, from its headwaters in northwestern Indiana to its confluence with Des Plaines River in northeastern Illinois. The complex origin of these deposits has been gradually unfolded as new data on the conditions of glacial drainage have been obtained. Most writers have associated all or part of these deposits with some sort of lake, but the character and geological relations of such a lake have never been definitely or satisfactorily determined. The present study is a contribution to the solution of the complex problem and suggests lines of further investigation.

[1] Manuscript received by the Secretary of the Society December 30, 1924.
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Paper read by the senior author.
Introduction by M. M. Leighton.

Probably the first geologic recognition of these deposits was incidentally recorded by Shepard,[2] who asserted that evidence of the occasional overflow of Lake Michigan at ancient periods exists along the Kankakee Valley. Later investigations have proved that this view of the relation with Lake Michigan is erroneous. Bradley[3] presented the first general description of the appearance and extent of the sand deposits and concluded that the Kankakee Valley is the basin of an extinct lake, which he called Lake Kankakee. Chamberlin[4] doubted the adequacy of Bradley's explanation and proposed as an alternative a "lacustral river." He pointed out that "this region must have been the avenue of discharge of vast quantities of water shed from the adjacent slopes of the great glaciers occupying the basins of Lakes Michigan, Huron, and Western Erie," and further suggested that the great accumulations of sand originated in this exceptional drainage but were subsequently modified by fluvial, lacustrine, and eolian action. Leverett,[5] [6] who doubtless has made the most comprehensive examination of this region, considered the area to have been occupied at first by several noncontemporaneous, marshlike lakes of small extent and shallow depth, on the borders of which there was outwash from successive positions of the fronts of the receding Michigan, Saginaw, and Erie ice-lobes. He further states that "the existence of certain low-lying tracts strewn with boulders and nearly free from sand, amid bordering higher sand-covered areas, suggests that patches of stagnant ice persisted while the sand was being laid down."[7] He considered that later, when the ice-lobes were at the positions shown in figure 4, the waters derived from their melting found an outlet and deposited additional sand along the Kankakee Valley.

Evidence obtained in 1923 by Ekblaw, during his detailed study and mapping of the Kankakee Quadrangle, Illinois, confirms Chamberlin's suggested explanation, refutes the existence at any time of a lake in the Kankakee Valley, at least in the vicinity of Kankakee and Momence, explains the boulder-strewn tracts as areas from which finer materials have been eroded, and involves a new conception of the drainage conditions during a part of glacial times.

[2] Charles Upham Shepard: Geology of Upper Illinois. American Journal of Science and Arts (Silliman's Journal), vol. 34, July, 1838, p. 137.

[3] Frank H. Bradley: Geology of Illinois, vol. iv, 1870, pp. 227, 236.

[4] T. C. Chamberlin: Preliminary paper on the terminal moraine of the second Glacial epoch. U. S. Geological Survey, 3d Annual Report, 1881-82 (pub. 1883), pp. 330-331.

[5] Frank Leverett: The Illinois Glacial lobe. U. S. Geological Survey, Monograph 38, 1899, p. 338.

[6] Frank Leverett and Frank B. Taylor: The Pleistocene of Indiana and Michigan and the history of the Great Lakes. U. S. Geological Survey, Monograph 53, 1915, pp. 128-130, 207, 219.

[7] Leverett and Taylor: Op. cit., p. 128.

Torrential bars composed of surprisingly coarse material and old channels were discovered at high levels. Over a wide stretch of territory the till has been removed with a consequent concentration of boulders. All the evidence points to a great torrent of glacial waters from the Michigan, Saginaw, and Erie lobes of the Wisconsin ice-sheet, which was discharged through the Kankakee Basin during the Valparaiso glacial stage. The ordinary drainage lines which were already developed could not accommodate this torrent, and it spread over the depression between the Marseilles moraine on the south and the later morainic belts on the north, stripping the bedrock of its drift mantle, heaping gravel and slabs of limestone into bars in the lee of rock hills, and depositing sands and silts in the quieter reaches along its outer border. This torrent is called the Kankakee Torrent and its discovery brings into clearer light the hitherto obscure conditions of drainage in the lower end of the Kankakee Valley.

During the summer of 1924 Athy found much corroborative evidence in his study and mapping of the Herscher Quadrangle, which adjoins the Kankakee Quadrangle on the west. He is able to point out the important bearing which the widespread waters had on the hitherto problematical sand deposits in the vicinity of Coal City and Dwight.

The composite results of these studies are summarized in this paper. The work in both quadrangles was performed under the auspices of the Illinois State Geological Survey and under the personal supervision of M. M. Leighton, Chief of the Survey, whose knowledge of the Pleistocene of northern Illinois enabled him to give much valuable help. The valuable comments and suggestions of Prof. Frank Leverett are also acknowledged.

Evidence of torrential Conditions

FOSSIL BARS

The most striking evidence of torrential conditions is presented by fossil bars. They are composed almost entirely of slabs and smaller fragments of local dolomitic limestone, with a small proportion of erratics. They vary in size from pebbles to flat slabs two feet or more in length and four to six inches thick, with cobbles and boulderets comprising the major part. Sand and silt are present only as interstitial filling. The pebbles are mostly crystalline erratics and are well rounded; the cobbles and boulderets are subrounded to subangular; and the larger slabs of limestone are angular, with little or no rounding on the corners and edges. The material is poorly sorted and the rude stratification appears to parallel the slope of the ridge in which it occurs. Some of the rubble

bars are completely covered with clean, uniform sand and are distinguished with difficulty from dunes unless their cores are exposed. This may explain why the true character of the bars was not discerned in the earlier and less detailed investigations. The best examples of this rubble are found in the western part of the Kankakee Quadrangle and in the eastern part of the Herscher Quadrangle.

The bars appear as isolated mounds or as single and combined ridges. They range from low swells, barely perceptible above the general flat, to conspicuous elevations forty feet high, where sand is piled up in dunes. They vary in width from a rod or two to over a quarter of a mile, and some are apparently united to produce a greater width. They may be only a few rods or as much as three miles in length, with a straight or slightly sinuous outline. The summits of most of the ridges are undulating, due either to irregular accumulations of the gravel and rubble or to development of sand dunes.

FIGURE 1.—*Gravel Pit in Rubble Bar in Section 17, Township 31 North, Range 11 East*
The size and angularity of the fragments, the poor sorting, and the rude stratification are well exhibited.

There is a pronounced parallelism in the alignment of the ridges, which are oriented in the direction of the current. Frequently some low rock remnant is found at the upstream end of the bars. This served to divide the current, and in the eddy behind it were deposited the large rock fragments which the torrent had ripped from the rock bed over which it rushed. In the interstices smaller fragments and sand and silt found lodgment.

ABANDONED HIGH-LEVEL CHANNELS

Across the moraines which form the walls of the Kankakee Valley are numerous channels whose floors are now between 630 and 660 feet in elevation. These channels vary in width from a quarter of a mile to over two miles. The small streams which now drain these valleys could

never have developed them. Abundant deposits of sand and gravel are found along some of them. One channel crosses the Marseilles moraine on the south side through a narrow gap just north of Chebanse. At its southern aperture is an abundance of sand and fine gravel. Another gap in this moraine is the broad, flat valley in which the present Iroquois River has incised itself. On the north side of Kankakee River a moraine younger than Minooka and older than Valparaiso is interrupted by side channels of the Kankakee Torrent, which are now occupied by Soldier, Davis, and Rock creeks. Behind this moraine a broad and well-developed valley runs northwest from Exline toward Manteno, and then westward along South Branch.

FIGURE 2.—*Detail of Rubble in Section 35, Township 31 North, Range 10 East.*

Note size, angularity, and poor sorting of materials.

EROSIONAL EFFECTS

The effects of erosion that the Kankakee Torrent would be expected to develop are as pronounced as those of deposition. The side channels have already been described. A steep bluff was cut by the torrent along the moraine at Kankakee and eastward to Exline. Another bluff appears to the east and becomes particularly pronounced at and east of Momence. Nearly all of the till that must once have been present in the Kankakee Valley was swept away by the torrent. At a few places where a road cuts through a ridge or mound, remnants of this till may be found beneath several feet of sand or gravel. The removal of the till bared the bedrock, and a smooth, relatively flat or gently undulating surface at about the 620-foot elevation was developed on it. Projections 10 to 30 feet high, in the lee of many of which are found sand or gravel deposits, were left above the general level of this surface. The surface of the rock has been weathered very slightly and shows no vidence of glacial action, such as polished or striated sur-

faces. In the areas between the fossil bars the rock is now covered with a mantle of sandy or silty soil varying in thickness from an inch or two to three or four feet. In these areas, also, boulders occur in abundance. Some of them are as much as 12 feet in diameter. Most of them are residual from the till which was swept away, although some may be ice-transported.

CHANGE IN TOPOGRAPHY AT LIMIT OF TORRENT

The lateral limits of the Kankakee Torrent are indicated by a considerable change in topography at a consistent line which can be traced around nearly the entire basin and which shows a downstream descent. Above that line the surface is irregular—partly morainic, partly erosional; below that line it approaches flatness, interrupted only by the fossil bars. At many places the exact limit can be definitely distinguished by a slight but abrupt break in slope.

ALLUVIAL DEPOSITS

Alluvial deposits of some sort are found everywhere in the Kankakee Basin below the upper limit of the Kankakee Torrent. The fossil bars of rubble, gravel, and sand, separated by areas of sandy or silty soil, have been described. Sand and gravel deposits are found along the abandoned channels. Sand or silt is found up to, but not above, the limit of the water on the slopes of the moraines which form the walls of the valley and in those areas where there were quiet reaches along the outside of the torrent. This silt and sand is grayish yellow, noncalcareous, with less than 2 per cent of small pebbles. The contact between the till and the silt is uneven and is generally marked by a thin layer of gravel, with pockets of coarse sand in the depressions.

CONSISTENT RELATION OF LEVELS

When assembling all of these evidences, the consistency of their upper limits becomes an evidence in itself. The rubble is never found above 660 feet. The abandoned channels are all below 670 feet. The till bluffs lose their steep slope above 660 feet. The change in topography occurs at a line that lowers from 660 feet in the east to 650 and 640 feet in the west. The alluvial deposits all occur below this line.

Supplementary Relations

Although the observations of the authors are limited to the local area represented by the Kankakee and Herscher quadrangles and the immediately contiguous territory, the interpretation that has been derived

applies to an extensive region. It is directly applicable to the whole of the main Kankakee Valley and to its immediate slopes. In Illinois the northern boundary of the main Kankakee Valley is formed by the moraine that is younger than Minooka and older than Valparaiso, although across and behind it are several side channels. These are in turn limited on the north by other morainic ridges. Farther east the Valparaiso and Kalamazoo moraines apparently form the northern bank of the torrent.

The conditions relating to the Kankakee Torrent are closely connected with a late phase of those relating to the flooding of the Iroquois Basin, which had an outlet through Vermilion River to the west at and possibly after the time the Marseilles moraine was being built. The Marseilles moraine, which formed in general the southern bank of the Kankakee Torrent and thus separated it from the Iroquois Basin, has gaps across it which allowed connections between the two basins when the floods were at high levels. This moraine also forms the constriction across the Illinois River valley, behind which the torrential waters were held until they reached a level at or slightly above 640 feet and consequently spread widely over the entire Morris Basin. Through this lacustral body of water a direct current was maintained from the Kankakee Valley to the outlet across the moraine. The sands and silts that now are found abundantly only in the southern part of the Morris Basin were deposited in the quieter water on the south side of the current. These deposits were supplied by the torrent but prevented by the current from being carried in any great amount to the north side of the basin. It may be found later that some of the beachlike ridges in the Morris Basin are related to some stages of the torrent. When the Morris Basin was flooded the lower parts of the Des Plaines and Du Page valleys were also filled to the same level.

The erosive action of the Kankakee Torrent may have developed the abrupt southern terminations of the Minooka till ridge, which separates the Morris and Des Plaines basins, and of the immense gravel deposits that form terraces along Des Plaines River. There is a possibility that the flat top of the southern part of the Minooka ridge, which is below the 640-foot level, resulted also from erosion by the torrent.

Nature and Extent of Torrent

The Kankakee Torrent extended from southern Michigan, across northwestern Indiana and northeastern Illinois, along Kankakee River, and then down Illinois River. The whole expanse of water varied in width from 5 to more than 12 miles. The depth of the cutting by the

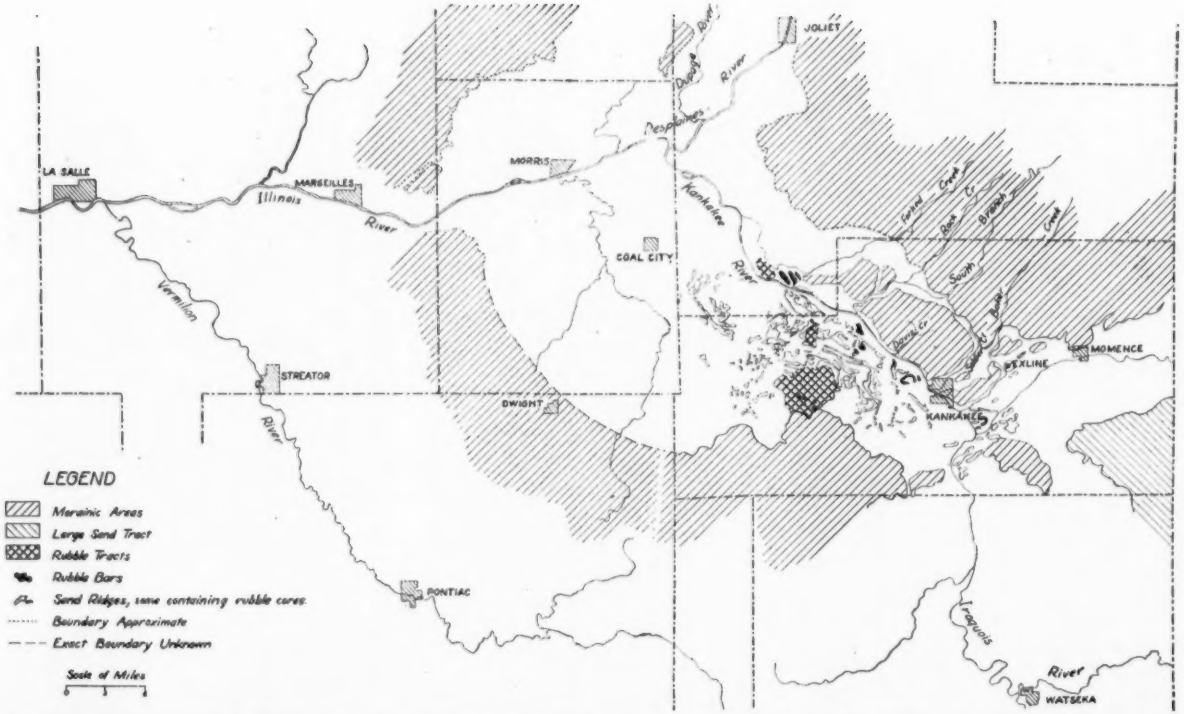

FIGURE 3.—*Map showing the Extent of the Area covered by the Kankakee Torrent in Illinois and the Parallelism of the Sand Ridges and Rubble Bars in the Kankakee and Herscher Quadrangles*

main torrent was aproximately 30 feet, as shown by the bluffs near Kankakee and Momence.

The torrent developed sufficient power to erode its channels cleanly and to carry material at least as coarse as that found in the rubble bars. The volume of water that was contributed created a current that flowed through the wide lacustral flood to and through the constriction in the Marseilles moraine. On the sides of the main current were quieter slack-water eddies. In the main current, wherever the current was checked, bars were developed; in the eddies the silts and fine sands were more

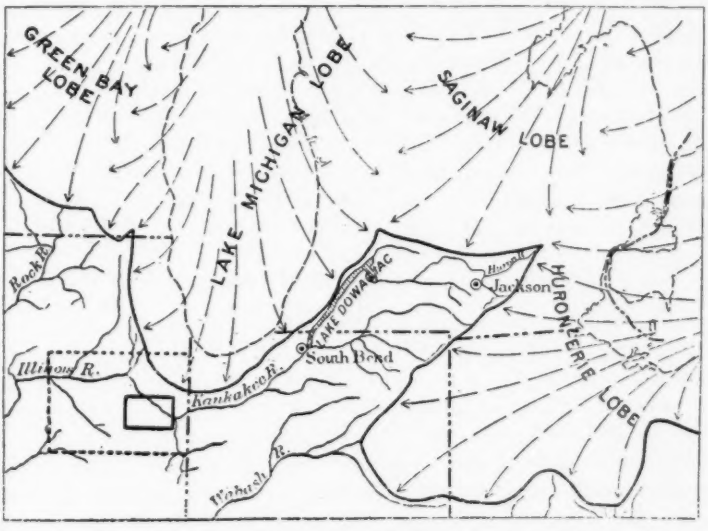

FIGURE 4.—*Map showing the Relation of the Michigan and Erie Ice-lobes to Kankakee River about the Time of the Kankakee Torrent*

The broken line includes the area shown in figure 3; the solid line outlines the Kankakee and Herscher quadrangles. (After Leverett.[8])

evenly deposited. As the torrent subsided, it assumed the appearance of a braided stream, and finally was confined to a single channel.

SOURCE OF WATER

This large volume of water was supplied by the Michigan, Saginaw, and Erie ice-lobes, whose unusual relations were first pointed out by Chamberlin.[9] Their interlobate contacts were the loci of an immense

[8] Frank Leverett: Ann Arbor Folio, Geologic Atlas of the United States, 1908.
[9] T. C. Chamberlin: Op. cit., pp. 328-330.

amount of crushing and crevassing—conditions that contributed to rapid melting and facilitated ready drainage from the interior of the ice. The surfaces of the glaciers sloped toward the interlobate areas and concentrated at their margins the discharge of all of the waters derived from the melting of areas far behind. The marginal melting was unusually rapid, also, as evidenced by the pitted outwash plains which Leverett and Taylor[10] found so abundant before the recessional moraines in Indiana and Michigan. All of these factors created a great volume of glacial waters, all of which had to pass down the Kankakee Valley. That avenue of discharge was used until the Michigan lobe had retreated far enough to permit Saint Joseph and Pawpaw rivers to cut through the moraines and divert their drainage into the incipient Lake Chicago and until the Erie lobe retreated far enough to free Wabash River to the south. The abundant outwash plains mentioned previously are evidence both of the great amount of drainage from the ice and of the great amount of debris present, which doubtless supplied much of the finer material that is found in the lower part of the Kankakee Basin and also in the Morris and Iroquois basins.

Age and History of Torrent

Since the Kankakee Torrent cut channels through and behind a moraine of the Wisconsin series younger than Minooka, it must be younger than that moraine. Streams that cut through later ridges to the north have along their banks abundant deposits of sand and gravel that appear to be correlated with those along the torrential channels, indicating that the torrent is younger than those moraines. It appears to be contemporaneous with the advance, halt, and retreat of the Michigan ice-lobe during the formation of the main Valparaiso moraine. In his description of the Camp Custer area,[11] Leverett shows that a great glacial stream occupied the Kalamazoo Valley and emptied into the Kankakee Valley during the formation of the Charlotte moraine. This moraine he considers the correlative of the Valparaiso moraine; so that the glacial river which he mentions was probably one of the headwaters of the Kankakee Torrent. The torrent ceased to exist before the opening of the Chicago outlet, for, in the valley of Illinois River, terraces belonging to the outlet succeed those belonging to the torrent.

When this volume of water was poured into the Kankakee Valley the Illinois River gap in the Marseilles moraine was an inadequate outlet for it, and it spread out over the adjacent territory until it reached a

[10] Frank Leverett and Frank B. Taylor: Op. cit.
[11] Frank Leverett: The Country around Camp Custer, 1918.

level grading back from the 640-foot elevation along the moraine. At that level the outlet was sufficiently large to allow an outflow that balanced the inflow. When the supply of water became less and the torrent began to subside, it may have assumed the appearance of a braided stream. As the several currents passed between the bars they deposited sand and silt on the flanks of the bars and, in the final stages, in the flats between the ridges. At last the waters were so decreased in volume that they were confined to a single channel, and as they continued to decrease they left successive terrace levels along the sides of the valley. Only the present Kankakee River, a dwarfed descendant of the Kankakee Torrent, now remains in the rock valley in which it has incised itself.

Conclusion

Although the Kankakee Torrent is firmly established in the opinions of the authors, much substantiating work remains to be done. The new interpretation has opened up new lines of study. Much information can be gained from a study of the upper Kankakee Valley. The Iroquois Basin presents a big problem. Undoubtedly it has been flooded, but the relations of this flood to the Kankakee Torrent are yet to be discovered. The history of its outlet through Vermilion River is an important problem in itself. The desirability of new studies in the Morris and Des Plaines basins has been suggested. A further study of Illinois River below Marseilles, and especially below La Salle, where Vermilion River flows into it, is necessitated. In fact, much of the history of the Late Wisconsin ice-sheet in this region is involved in the solution of the numerous ramifications of the problem which is introduced by the discovery of the Kankakee Torrent.

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PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

BURIED INDIAN WORKSHOP WITH REMAINS OF AN EXTINCT MAMMAL[1]

BY WILLIAM A. PARKS

(Presented in abstract before the Paleontological Society Dec. 30, 1924)

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INTRODUCTION

In the summer of 1923 Doctor J. J. Finn, of Dundurn, Saskatchewan, while trying to ascertain the nature of the bottom of a bog on his property, secured numerous fragments of bone and a number of teeth, which were submitted to the writer for determination. While some of these remains were easy of identification, others were beyond the experience of the writer. The assistance of Doctor W. D. Matthew was solicited, and to him belongs the credit of recognizing the Antilocaprid affinities of the teeth herein described.

In 1924 a visit was made to Doctor Finn's property in the hope that an excavation could be made to the bottom of the bog, but it was found to be impossible to accomplish this object, as the muck and sand flowed into the hole as fast as it could be removed by the means available. Nevertheless, by the aid of an improvised scoop, the bones and teeth secured by Doctor Finn were supplemented by a much larger collection, and the organic remains were found to be associated with objects of Indian workmanship.

LOCATION

The city of Saskatoon is situated in the Province of Saskatchewan, at the junction of the north and the south branches of the Saskatchewan

[1] Manuscript received by the Secretary of the Society March 10, 1925.

River. The bog lies about 15 miles south of Saskatoon and 5 miles north of the town of Dundurn. It is about 100 yards in diameter, but opens out on one side into a larger swampy tract that drains away to the Saskatchewan River. The surface muck is sufficiently consolidated by vegetable matter to permit one to walk over most of its extent. In three places, however, springs of potable water arise through the muck and seem to have a small but constant flow.

A section of the bog indicates a depth of ten feet, the upper four feet being of muck and the lower six feet of sand, with small fresh-water gastropods. The bottom of the sandy layer is coarse and gravelly, with occasional large pieces of stone. It was in this lower layer that the associated teeth and objects of Indian workmanship were found. The bottom of the bog is of a tough, yellowish clay identical with that of the surrounding prairie.

Indian Workmanship

The bones have all been broken artificially and in many instances they show evidence of having been scraped with stone knives. Many of the Indian objects are incomplete; for example, arrow heads were found in all stages of preparation, from mere flint chips to the completed article. There can be little doubt that at an early date a spring of good water issued from the clay at the bottom of the depression, thus affording a desirable site for a camp. Around the spring the Indians worked and feasted, leaving a rich record of their activities in both these pursuits. At a later date, by a choking of the drainage, the depression was converted into a pond, as indicated by the fresh-water mollusks. In this pond wind-blown sand accumulated to a depth of six feet. With a reduction of the water, the pond passed into the condition of a bog, in which muck has since accumulated to a depth of four feet.

The following is a rough list of the Indian material secured:

38 pieces shell wampum.
16 pieces fish vertebræ pierced for wampum.
3 pieces shell partially made into wampum.
2 ornaments of shell (dolls' faces?).
5 pieces shell partially worked.
Arrow heads.
4 finished, but of rough workmanship.
9 imperfectly finished.
11 roughly shaped.
6 merely blocked out.
9 knives or tools of flint.
75 flakes of flint, etcetera, including three of obsidian.
131 hand-broken fragments of flint and other stone.
32 fragments of stone, possibly natural.

3 pendants or beads—elk's tooth, claw, stone.
1 flute or whistle made from a shaft bone.
1 pestle of dolomite.
1 stone for pounding or grinding.

The arrow heads are made of the following rocks: two of pink quartzite, six of black flint, nine of quartzite or vein quartz, eight of brown flint, five of a softer black rock. In addition, several other rocks are indicated by the fragments, including black obsidian.[2]

The bones and teeth may be divided into two groups, according to the condition of preservation. The bones of one group are black in color and frequently coated with a film of pyrite; those of the other group are quite fresh in appearance. It is possible, even probable, that the latter were derived from the upper muck layers. The method of collecting—by scooping under ten feet of water—makes it impossible to determine the exact level from which a specimen has been secured. It is noteworthy, however, that all the hand-broken fragments of bone are black.

Organic Remains

The organic material may be listed as follows:

Nearly a half-bushel of broken fragments of bone.
16 mandibular molars and premolars of buffalo.
10 maxillary molars and premolars of buffalo.
4 milk molars of buffalo.
22 incisor teeth, indeterminate as to species; some buffalo.
1 molar of caribou?
1 molar of badger.
2 ends of fibula, probably of buffalo.
2 sesamoid bones.
1 premolar of wolf.
1 canine of bear.
1 atlas of buffalo.
2 mandibles of small rodents.
A large number of broken teeth, toe bones, and other material of doubtful identification.
3 molars and one incisor of the antilocaprid described herein.

[2] In volume 1 of the Bulletin of the Geological Society of America, page 406, Mr. J. B. Tyrrell makes the following statement: "On Valley River, in lat. 51° 13′ N., long. 100° 20′ W., at a distance of two feet below the surface, some roughly chipped fragments of quartzite have been discovered, lying horizontally among the disk-shaped waterworn pebbles, along with a small bone of a mammal. Precisely similar fragments are now to be found on the shores of lakes Winnipegosis and Manitoba in association with well-formed arrow-points, and the traditions of the Indians go back to the time when they were formed and used by their forefathers. As the gravel had been laid down by water action and was quite undisturbed, they clearly indicate the existence of man at the time when this lake beach was being thrown up, and it is probable that here, near the mouth of the former representative of Valley River, was one of his favorite haunts."

When it is remembered that all this material was obtained in an area of about two square feet, the possibilities of the bog for the yielding of large and valuable collections would seem to be considerable.

Neomeryx finni, a new Genus of Antilocaprid [3]

The type material consists of the three right mandibular molars and one incisor. The two anterior molars and the incisor are nearly perfect, but the third molar is so broken that the superior surface can not be observed.

Number 20,502, Royal Ontario Museum of Palæontology

The prong-horn *Antilocapra americana* is the only generally recognized representative of the family *Antilocapridæ* now living, and it has frequently been found in the Pleistocene of America. Authors are not in accord with regard to the fossil genera that should be included in this family, but there is little doubt that the only important genera are *Merycodus* and *Capromeryx*. The species of the former genus recognized as valid by Matthew are as follows:[4]

Merycodus necatus Leidy. Bijou Hills, Middle Miocene.
Merycodus necatus sabulonensis Matthew and Cook. Snake Creek, Upper Miocene
Merycodus osborni Matthew. Pawnee Creek, Upper Miocene.
Merycodus warreni Leidy. Valentine, Lower Pliocene.
Merycodus ramulosus Cope. Santa Fe, Lower Pliocene.
Merycodus furcatus Leidy. Valentine, Lower Pliocene.
Merycodus altidens Matthew. Upper Snake Creek, Pliocene.

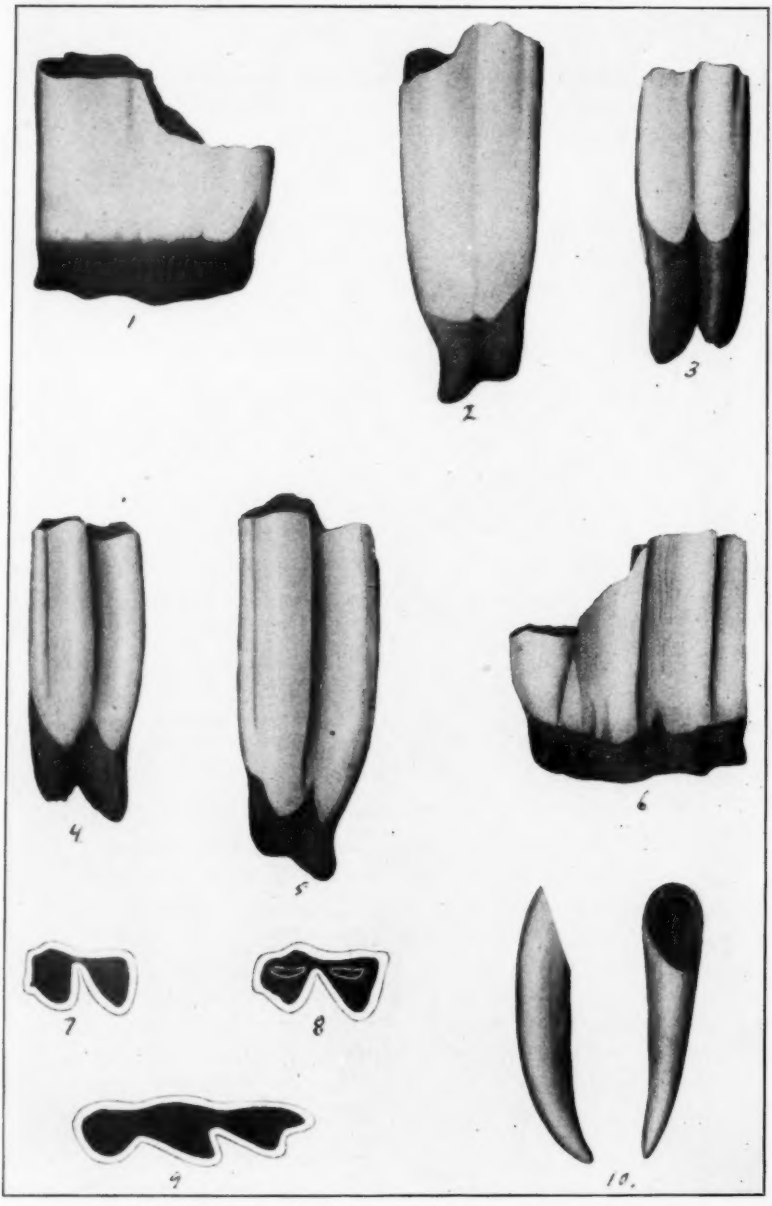
The genus *Capromeryx* is represented by two species only:

Capromeryx furcifer Matthew. Pleistocene of Hay Springs, Nebraska.[5]
Capromeryx minor Taylor. Pleistocene of Rancho La Brea.[6]

In addition, mention should be made of species described by Merriam as Strepsicerine antelopes, but without definite reference to the *Antilocapridæ—Ilingoceras alexandræ* and *Sphenophalos nevadanus* from the late Tertiary of Nevada.[7]

The teeth under review are so like those of *Antilocapra* that there can be little doubt as to their family relationship. As the teeth of Merriam's genera are unknown, a comparison is obviously impossible. The absence

[3] Specific name for Dr. J. J. Finn, of Dundurn, Saskatchewan, the discoverer of the type material.
[4] Bull. Am. Mus. Nat. Hist., vol. I, Art. II, 1924.
[5] Bull. Am. Mus. Nat. Hist., vol. xvi, 1902.
[6] Univ. California, Bull. Dept. Geol., vol. vi, no. 10, 1911.
[7] Univ. California, Bull. Geol. Dept., vol. v, no. 22, 1909.



RIGHT MANDIBULAR MOLARS AND ONE INCISOR OF NEOMERYX FINNI

All Figures × 2.4

FIGURE 1.—Third molar, external view.
FIGURE 2.—Second molar, external view.
FIGURE 3.—Third molar, external view.
FIGURE 4.—First molar, internal view.
FIGURE 5.—Second molar, internal view.
FIGURE 6.—Third molar, internal view.
FIGURE 7.—First molar, upper view.
FIGURE 8.—Second molar, upper view.
FIGURE 9.—Third molar, upper view.
FIGURE 10.—Incisor, lateral and internal views.

of rugosities on the teeth removes the present species from the *Cervidæ;* consequently a relationship with forms like *Blastomeryx, Dyseomeryx,* and *Dromomeryx* is not indicated. The inquiry, therefore, narrows down to a comparison with *Antilocapra, Capromeryx,* and *Merycodus.*

The three molars are strongly hypsodont and very similar to the corresponding teeth of *Antilocapra* in general pattern and dimensions. In the latter respect they differ by only a half millimeter.

Measurements of Molars of Neomeryx

	Total height. *Millimeters.*	Height of crown. *Millimeters.*	Width of crown. *Millimeters.*	Length of crown. *Millimeters.*
M_1	28	22.5	7.5	12
M_2	36.5	30	8.5	14
M_3	....	....	8.5	25

M_1 and m_2 (figures 2, 3, 4, 5, 7, 8) differ from the corresponding teeth of *Antilocapra* in the following way:

Externally the two lobes are more rounded and better defined by a vertical furrow between them.

The external angles are less sharp, owing to the absence of the vertical fluting seen in *Antilocapra.*

Internally the two lobes are less angulated and the anterior lobe carries a pronounced vertical furrow, suggesting the incipient development of a third lobe anteriorly. This feature alone sharply differentiates these teeth from those of *Antilocapra.*

Crescentic lakes in the crown are seen only in m_2; they are less extended externally than in *Antilocapra.* As the tips of the crescents in this genus are in relation to the vertical fluting on the external surface of the tooth, the absence of the latter feature in *Neomeryx* is in accord with the more feeble development of the lakes. In both teeth the superior view shows a slight angulation on the anterior lobe in accord with the vertical furrow already referred to.

M_3 (figures 1, 6, 9) is so broken that only the lower half of the crown is available for description. The outer surface is remarkably smooth and flat, the lobes being quite undefined and the anterior and posterior angles rounded. Internally the three anterior lobes are well defined, more rounded, and with a greater backward inclination from the longitudinal plane of the tooth than in *Antilocapra.* As only about 8 millimeters of the crown of the anterior lobe is preserved, the vertical furrow observed in the other two teeth is not revealed. There is, however, a slight indication of its presence, and there is little doubt that it was as well developed as in the other two molars. The small fourth lobe is clearly defined internally and is as well developed as in *Antilocapra,* but, as already

stated, its presence would not be suspected from an external view, as it would in *Antilocapra*.

The superior view shows no internal lakes, although the substance of the tooth is sufficiently preserved to reveal them if they existed. It is possible that the lakes came in at a higher level, but the general evidence is to the contrary. This conclusion is supported by the smooth nature of the outer surface, which is in strong contrast to the ribbed surface of the *Antilocapra* tooth, in which well-developed concentric lakes are present.

It is apparent that in those features which particularly characterize *Antilocapra* the present teeth represent a less advanced stage of development. On the other hand, the incipient development of an extra lobe in the anterior position points to a separate line of development and justifies the erection of a new genus.

The incisor tooth (figure 10) is provisionally referred to the same species. The color and the condition of preservation are identical. The tooth can not be distinguished from the corresponding tooth of *Antilocapra*.[8]

The present genus can scarcely be confused with *Capromeryx*, as the two described species of that genus are only two-thirds the size of *Antilocapra*, while *Neomeryx* is fully as large. Further, the teeth of *Capromeryx minor* are thus described:

"Permanent m_1 and m_2 are so similar to those of *Antilocapra* that no points of difference in them can be picked out, so far as form is concerned. M_3, however, is more primitive than m_3 of *Antilocapra* in the inferior development of the fourth lobe or heel. While in the modern species this tooth normally has a very distinct fourth lobe, in *Capromeryx* this is only suggested by a slight elongation of the third lobe."[9]

The present genus differs from *Merycodus* in the greater degree of hypsodonty and the better development of the fourth lobe on m_3. It approaches most closely to *M. altidens* Matthew, but differs from that species in many details. From *M. necatus* Leidy, the type of the genus, our species differs widely, particularly in that the genotype shows no trace of a fourth lobe on m_3.[10]

[8] The comparisons with *Antilocapra* were made by means of Specimen No. 11094, kindly loaned by the American Museum of Natural History.

[9] Univ. California, Dept. Geol. Bull., vol. ix, no. 10, 1916.

[10] Extinct mammalian fauna of Dakota and Nebraska, 1869, pl. xiv, figs. 9 and 10.

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CRETACEOUS AND TERTIARY FORMATIONS OF THE WASATCH PLATEAU, UTAH *

BY EDMUND M. SPIEKER AND JOHN B. REESIDE, JR.

(*Read before the Geological Society December 30, 1925*)

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INTRODUCTION

This paper is intended to present, in summary fashion, some of the results of stratigraphic work by the senior author in the Wasatch Plateau of Utah. In this study he has had the advantage of extensive conference, both in the field and in the office, with the junior author, who contributes

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to the paper the paleontologic part of the work and many of the comparisons with other regions.

General Features of Plateau

Location and surface features

The Wasatch Plateau lies in central Utah. It is the northeastern unit of the great group of high plateaus that borders the northern part of the Colorado Plateau on the west and separates it from the Great Basin. The plateau is a fairly well-defined tableland, about 90 miles long and 20 to 30 miles broad, whose summits commonly reach elevations 10,000 to 11,000 feet above sealevel and 5,000 to 6,000 feet above Castle Valley on the east and Sanpete and Sevier valleys on the west. Castle Valley is entirely erosional in origin and it represents a broad platform in the great steplike succession of benches rising from the Colorado River to the High Plateaus. Sanpete and Sevier valleys, on the other hand, are primarily structural in origin and are due to a great downfolded and faulted block that parallels on the west the eastern tier of the High Plateaus. On the north the Wasatch Plateau merges with the higher land at the western end of the Uinta Basin; on the south it is separated from the Fish Lake Plateau by an erosional depression about 20 miles broad. The location of the plateau is shown on the index map, figure 1.

Structure

In the eastern part of the plateau the formations lie nearly level or dip gently westward. The basal slopes are made by Mancos shale, above which are cliffs of sandstone and shale of the Mesaverde group; and above them in turn, forming the summits, the Wasatch formation. On the western flank the beds plunge downward in a huge monocline that borders on the east the first of the great series of faults in the structural province of the Great Basin. This western border presents great dip slopes, chiefly in the beds of the Wasatch formation, but locally of the underlying Cretaceous. In places within the plateaus the rocks are broken by zones of normal faults, some of them rather complex.

Mancos Shale

General statement

The Mancos shale here consists of five well-defined members, as shown in the columnar section for the southern part of the Wasatch Plateau. The lower two members do not really form the surface of any part of the plateau, but are well shown in the adjacent valleys and certainly underlie the plateau.

LOWER SHALE MEMBER

The lowest member, unnamed, is a gray marine shale about 600 feet thick, with *Gryphea newberryi, Inoceramus labiatus, Metoicoceras,* and other fossils characteristic of a widespread faunal zone in the lower part

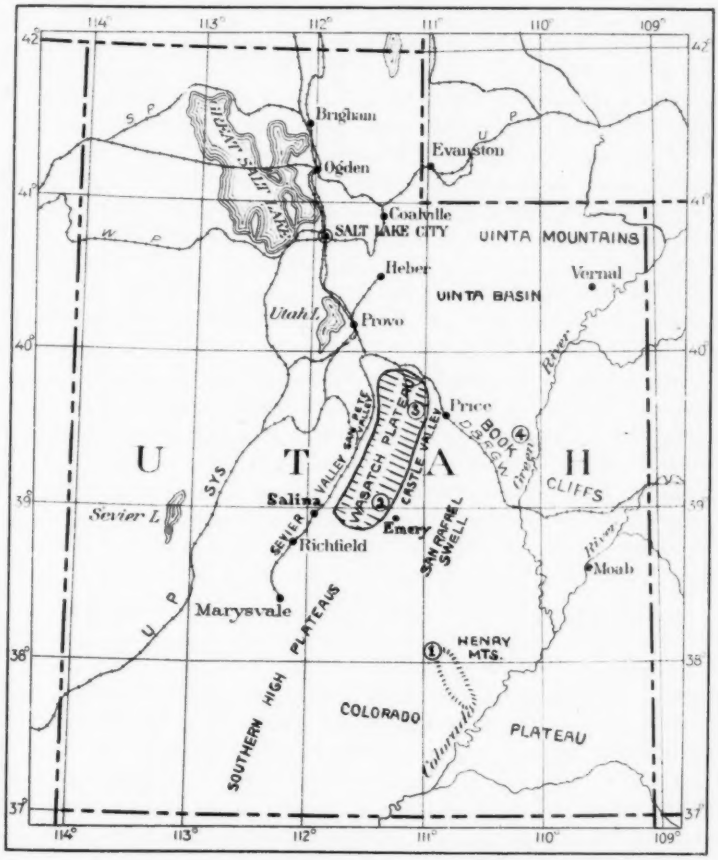

FIGURE 1.—*Index Map of Utah, showing Location of Wasatch Plateau*

Numerals in circles indicate location of sections given in figure 2.

of the Colorado group. It is equivalent to the "Tununk shale" of Gilbert's section in the Henry Mountains and to the Graneros and Greenhorn formations east of the Rockies. This shale underlies the eastern

part of Castle Valley and borders the San Rafael Swell. Locally it rests on a sandstone that has been called Dakota, but at many places it is in direct contact with variegated beds probably of Morrison age (upper part of the McElmo formation of many geologists).

FERRON SANDSTONE MEMBER

The next higher member, the Ferron sandstone, fully described by Lupton[1] and Clark,[2] is a variable group of brown sandstone, gray shale, and local coal beds. It contains a fauna, with such species as *Scaphites warreni, Prionocyclus wyomingensis, Prionotropis hyatti, Inoceramus fragilis, Inoceramus dimidius,* and *Ostrea lugubris,* that correlates it with a widespread zone in the Colorado group especially well typified by the Carlile shale east of the Rockies. It is the faunal equivalent of the Tununk sandstone of Gilbert's section in the Henry Mountains.

The Ferron sandstone contains considerable coal at the southern end of Castle Valley, but north of Emery, 60 miles south of the Denver and Rio Grande Western Railroad, coal is lacking at the outcrop. The sandstone also thins northward along the outcrop from a thickness of 700 feet south of Emery to 50 feet near Farnham. A recent drilling near Price, on the Denver and Rio Grande Western Railroad and 10 miles west of the outcrop, shows the sandstone to be 200 feet thick there and to contain several beds of coal, one of which is 7½ feet thick. The regional tendency of the Cretaceous beds to change westward from marine to littoral, to continental and coal-bearing sediments, is well shown by this occurrence.

MIDDLE SHALE MEMBER

Above the Ferron sandstone is the middle member of the Mancos, a gray marine shale, also unnamed. It ranges in thickness from 1,650 feet at the south end of the Wasatch Plateau to 2,650 feet at the north end. Farther east, along the Book Cliffs, it is inseparable from the upper member. Within the Castlegate Quadrangle, at the northern end of Castle Valley, this shale contains in the upper part a lenticular sandstone named by Clark in his unpublished paper the Garley Canyon sandstone member of the Mancos shale. Much, if not all, of the middle shale member is Niobrara in age, and it contains at a number of horizons such distinctive fossils as *Scaphites vermiformis, Scaphites ventricosus, Inoceramus deformis, Inoceramus undulatoplicatus,* and other undetermined but very large species of *Inoceramus.*

[1] C. T. Lupton: The geology and coal resources of Castle Valley, Utah. U. S. Geol. Survey Bull. 628, 1916.

[2] F. R. Clark: The geology and coal resources of the Sunnyside, Wellington, and Castlegate quadrangles. U. S. Geol. Survey Bull. in preparation.

EMERY SANDSTONE MEMBER

The next member in the Mancos shale is a sandstone here designated the Emery sandstone member, best developed at the southern end of the field, southwest of the town of Emery, where its steplike cliffs of brown sandstone border a pronounced platform beneath the major cliffs of the Wasatch Plateau. This sandstone was described by Lupton as the Mesaverde formation and was considered by him to be faulted down to its present position beneath the cliffs. The present work, however, showed conclusively that it is a member of the Mancos shale. The Emery sandstone member is 800 feet thick near Emery, and is considerably thicker 15 miles farther south, but it thins northward and splits into two tongues similar to the tongues of the lowermost Mesaverde, discovered by F. R. Clark in the western Book Cliffs. The upper tongue, as shown in the graphic sections (figure 2), is the only representative in the Castlegate Quadrangle, described by Clark,[3] of the Emery sandstone member, for the lower tongue dies out near the northern end of the Wasatch Plateau. The Emery sandstone contains a large fauna—mostly undescribed, but also including such species as *Inoceramus lobatus, Pteria nebrascana, Thetis subcircularis, Tellina equilateralis,* and *Placenticeras planum*—that shows it to be at the base of the Montana group and approximately equivalent to the basal Pierre east of the Rockies, the Steele shale of Wyoming, and the Eagle sandstone of Montana. It is probably not of the same age as the Bluegate sandstone[4] of the Henry Mountains, but is more likely equivalent to the lower part of the Masuk sandstone of that region, though fossils are not on record from either of these sandstones and a certain correlation is not yet possible.

UPPER SHALE MEMBER

The upper member of the Mancos is a third gray marine shale, very prominent north of Emery and attaining a thickness of 1,100 feet. It thins southward along the plateau front to 600 feet and is probably still thinner beyond that point. It is possible that the shale interval has changed entirely to sandstone in the southern plateaus and the Henry Mountains. The Masuk sandstone may thus represent the Emery sandstone and the upper shale member of the Mancos, but sufficient evidence for correlation is not yet in hand. The upper shale member has yielded a few fossils not more closely assignable than to the Montana group.

The thicknesses and stratigraphic relationships of the members of the Mancos shale are shown graphically on figure 2.

[3] F. R. Clark: Op. cit.

[4] G. K. Gilbert: The geology of the Henry Mountains. U. S. Geol. and Geog. Survey Rocky Mt. Region, 1880, pp. 3-10.

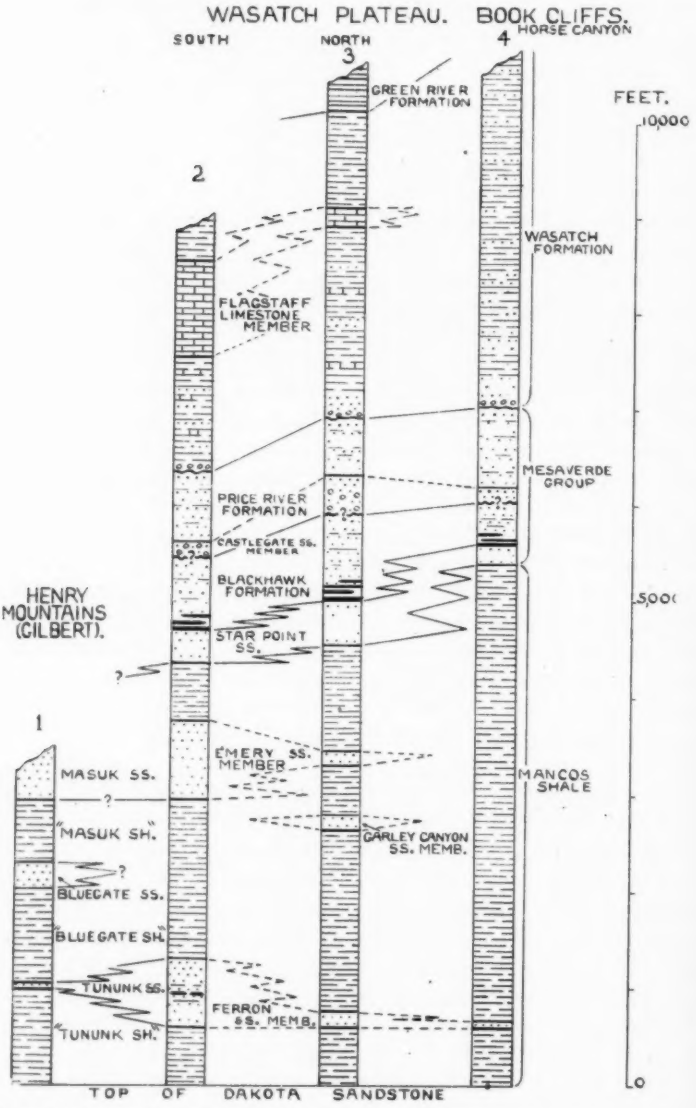

FIGURE 2.—*Columnar Sections of the Cretaceous and Tertiary Formations of the Wasatch Plateau and adjoining Regions*

MESAVERDE GROUP

THE MESAVERDE GROUP IN COLORADO, NEW MEXICO, AND UTAH

The Mesaverde formation, or group, first defined by Holmes[5] in the Mesaverde of southwestern Colorado, consists in the type area of a basal marine sandstone; a middle unit of sandstone, shale, and coal beds, in part marine and in part brackish and fresh-water sediments, and an upper marine sandstone. It is thus chiefly a marine series of shale and sandstone, with some coal and some nonmarine beds in the middle part. It is underlain by the marine Mancos shale and overlain by the marine Lewis shale. The Lewis shale is followed in turn by the marine Pictured Cliffs sandstone and the nonmarine Fruitland and Kirtland formations, all assigned to the Montana group. South of the type locality the Lewis shale thins and practically vanishes,[6] and the Mesaverde and succeeding formations do not contain a large body of marine shale, although a very thin Lewis may be identified, and most of the sandstones up to the base of the Fruitland formation are marine. Since the Mesaverde thickens progressively as the Lewis thins, it is clear that the thinning is by change of the shale laterally into sandstone.

North of the Mesaverde erosion has removed the group from a large area, and the next place where the name has been applied is in the Grand Mesa, in western Colorado. Here the lowest beds are marine (Rollins sandstone member of Lee[7]), followed, in upward succession, by beds with some marine, though predominantly brackish water, fossils (Bowie shale member of Lee), then by apparently unconformable beds with plants and chiefly fresh-water invertebrates (Paonia shale member of Lee and undifferentiated Mesaverde of Lee), and these in turn by unconformable Tertiary beds. There is no marine shale comparable to the Lewis shale of San Juan Basin. The brackish water fossils are identical with those occurring farther west in the coal-bearing Mesaverde of the Book Cliffs and in part like those of the Fruitland formation. The fresh-water species are much like those of the Fruitland. Lee suggested that his two uppermost members of the Mesaverde might eventually prove to be of the age of the so-called Laramie of adjacent regions north and south of Grand Mesa, and that the unconformity noted might be of more than local importance and represent the marine Lewis of these other regions.

The succession of beds included in the Mesaverde of Grand Mesa has

[5] W. H. Holmes: Geological report on the San Juan district. U. S. Geol. and Geog. Survey Terr., Ninth Ann. Rept., for 1875, pl. 35, 1877.

[6] J. B. Reeside, Jr.: Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin. U. S. Geol. Survey Prof. Paper 134, 1924, p. 17 and fig. 3.

[7] W. T. Lee: Coal fields of Grand Mesa and West Elk Mts., Colo. U. S. Geol. Survey Bull. 510, 1912, pp. 29-47.

been traced by Gale,[8] Richardson,[9] and others, in general but not in detail, into northwestern Colorado and westward along the Book Cliffs into central Utah. Throughout this area the homogenetic equivalence of the series seems certain, and, excepting the Mesaverde in parts of the Yampa region of Colorado, where there is a marine shale assigned to the Lewis, a gross similarity in age seems reasonably certain. In the Yampa region the chiefly nonmarine Mesaverde is overlain on the north limb of Axial Basin anticline by a marine shale commonly correlated with the Lewis and a nonmarine series usually called "Laramie"; on the south limb a much thicker Mesaverde is succeeded immediately by beds of Fort Union age, which are called post-"Laramie" formation. Sears,[10] who has recently studied the region, believes that the thicker Mesaverde of the south limb represents the Mesaverde, Lewis, and "Laramie" of the north limb, and that the Lewis has changed from marine shale to nonmarine sandy beds—a change somewhat analogous to that described for the San Juan Basin. Other geologists, however, believe that the evidence now available is insufficient to disprove the view expressed by Gale, that erosion removed the "Laramie" and Lewis, and that the Mesaverde on both sides of the anticline is the same.

The name Mesaverde has been carried still farther north into areas which are of little importance in the present discussion other than to emphasize the rather widespread and loose usage the name has had and its present significance of lithology rather than time.

SUBDIVISIONS OF THE GROUP IN THE WASATCH PLATEAU

In the Wasatch Plateau the rocks designated the Mesaverde group are subdivided into three formations: a basal sandstone of littoral marine origin, here called the Star Point sandstone; a middle coal-bearing formation of brackish and fresh-water sediments, probably laid down in a swampy coastal area, here called the Blackhawk formation; and an upper formation of chiefly fresh-water sediments, in large part probably fluviatile in origin, here called the Price River formation. These rocks form the main escarpments of the Book Cliffs and the east front of the Wasatch Plateau.

STAR POINT SANDSTONE

The upper shale member of the Mancos passes by gradual transition into the basal formation of the Mesaverde group, the Star Point sand-

[8] H. S. Gale: Coal fields of northwestern Colorado and northeastern Utah. U. S. Geol. Survey Bull. 415, 1910.

[9] G. B. Richardson: Reconnaissance of Book Cliffs coal field. U. S. Geol. Survey Bull. 371, 1909.

[10] J. D. Sears: Geology and oil and gas prospects of part of Moffat County, Colo., and southern Sweetwater County, Wyo. U. S. Geol. Survey Bull. 751-G, 1924, p. 290.

stone, whose thickness ranges from 200 to 450 feet. The name of this formation is derived from Star Point, a striking headland of the Wasatch Plateau southwest of Price, in which their sandstone is fairly prominent. The Star Point sandstone really represents the retreating or closing phase of the Mancos sea and is more closely allied in origin with the Mancos than with the Mesaverde type of rocks, but it is included in the Mesaverde in conformity with the accepted practice of giving that name to the sandstones of Montana age immediately overlying the Mancos shale. The chronologic value of the names Mancos and Mesaverde is so variable from place to place that it is not of great importance whether the Star Point sandstone be assigned to one or the other.

Clark[11] has shown that the Star Point sandstone of the Wasatch Plateau is equivalent in time to the upper part of the Mancos shale of the Book Cliffs, and that it splits eastward into three tongues of sandstone penetrating into the Mancos, the eastern ends of which are not far from the boundary of the Wasatch Plateau. The Star Point type of sediment is continuously present at the base of the Mesaverde eastward along the Book Cliffs.

The Star Point sandstone thus affords a good example, in its relation to the basal Mesaverde of the Book Cliffs, of what Lee[12] has called a homogenetically equivalent unit. It is safe to say that 1,000 feet, and possibly more, of sandstone in the north central part of the Wasatch Plateau is contemporaneous with a similar amount of shale in the upper part of the Mancos of the western Book Cliffs, and if the exposures in the cliffs were not so good as to reveal unmistakably the intertonguing of shale and sandstone, the Star Point sandstone might be "traced" directly into sandstones of exactly similar appearance and relation to the Mancos shale, but 1,000 feet higher stratigraphically.

A few exposures of the Star Point sandstone west of the eastern front of the Wasatch Plateau, chiefly in Pleasant Valley and in Huntington Canyon, show that it thickens rapidly westward and accordingly add to the increasing sum of evidence showing that the western shore of the Mancos sea was, in general, not far west of the present Wasatch Plateau.

BLACKHAWK FORMATION

The Blackhawk formation, so named because it is prominently exposed near the Blackhawk mine, a prominent mine on the eastern front of the Wasatch Plateau, is a well-defined unit of buff sandstone, shale, and coal of the kinds common in the Mesaverde group throughout the southwest.

[11] F. R. Clark: Op. cit.

[12] W. T. Lee: Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico. U. S. Geol. Survey Prof. Paper 95-C, 1915, p. 29, fig. 12.

It is 750 to 900 feet thick in the plateau, but thins to about 450 feet in the Book Cliffs. The Blackhawk formation lies conformably on the Star Point sandstone, and the lowest coal bed of the field is normally taken as its base. Many fossil plants, determined by Dr. F. H. Knowlton to be Mesaverde (that is, Montana) in age, have been found in the formation, but so far very few invertebrate fossils have been found in the formation in the Wasatch Plateau. However, the directly continuous beds of the Book Cliffs field contain a few marine species and much more abundant

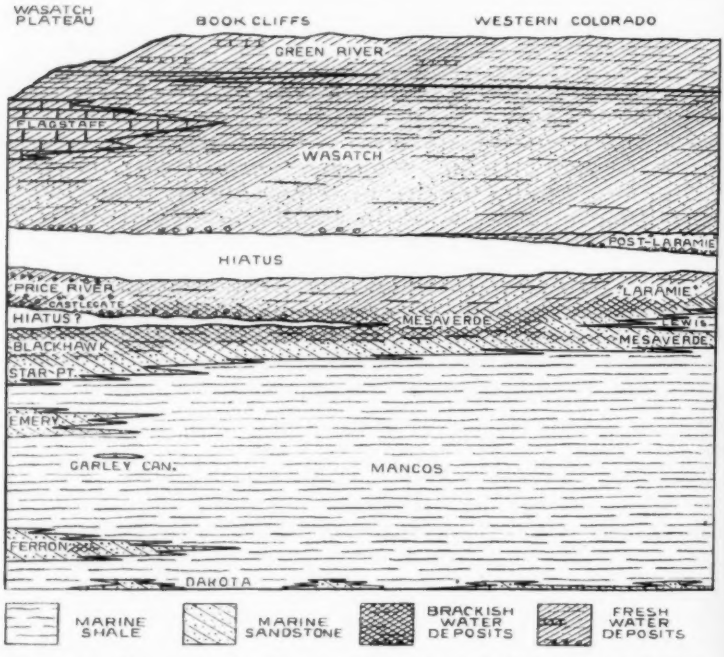

FIGURE 3.—*Diagram showing the general Relations of the Cretaceous and Tertiary Formations of central Utah and western Colorado, as interpreted in this Paper*

brackish water species of mollusca, including such forms as *Ostrea glabra, Anomia micronema, Modiola laticostata, Corbicula cytheriformis, Panope simulatrix, Corbula undifera, Corbula subtrigonalis, Melania insculpta.* There have also been found a few individuals belonging to the fresh-water genera *Viviparus, Campeloma,* and *Unio.*

The graphic sections on figure 2 and the stratigraphic diagram, figure 3, show the relationship of the Blackhawk formation to parts of the

Mesaverde group farther east and south. The work of Clark has shown the lower part of the unit here called Blackhawk to change eastward to littoral sandstone of the Star Point type, and to wedge out still farther eastward in tongues projecting into the Mancos shale. The upper part of the formation, however, is equivalent to the lower part of the Mesaverde, as defined in eastern Utah and western Colorado. Its exact relation to the formations of the southern High Plateaus is not known.

PRICE RIVER FORMATION

Above the Blackhawk formation lies a succession of predominantly gray sandstones, grits, and conglomerates, with a minor amount of shale, here designated the Price River formation. The type exposures of the formation are in the canyon of Price River above Castlegate, Utah. The formation consists of a massive basal member, the Castlegate sandstone member of Clark[13]—a coarse, sugary, white to brown, quartzose sandstone, with lenses of pebbles of quartz and chert—and an upper member which is normally similar in lithology to the Castlegate member, but is less massive and forms slopes rather than cliffs. The Castlegate member ranges in thickness from 150 to 400 feet and the overlying part of the formation from 600 to 800 feet, the total thickness ranging from 900 to 1,000 feet.

The upper boundary of the formation is reasonably sharp at most places, due to contrast in lithology and the presence locally of an overlying conglomerate of limestone pebbles. On the western border of the Wasatch Plateau the writers have seen ample evidence of a post-Price River orogenic movement. In this disturbance the rocks up to and including the Price River formation were folded by intense compression, their upturned edges were eroded, and the rocks here designated the Wasatch formation were laid down unconformably on the resulting surface.

The nature of the lower boundary is open to question. The actual contact between the Blackhawk and Price River formations, owing to the talus from the cliff of Castlegate sandstone, is neither so accessible nor so well exposed as are most other geologic horizons in the area, and the writers have therefore not seen as much of it as might be desired. The lithologic contrast between the fine-grained, predominantly buff beds of the Blackhawk and Star Point formations and the coarse, predominantly gray beds of the Price River formation is strong. In all of the Wasatch Plateau and the neighboring parts of the Book Cliffs the Castlegate sandstone contains abundant conglomerate, and the upper member is in places

[13] F. R. Clark: Op. cit.

even more markedly conglomeratic. At only one locality, on the divide between North Gordon Creek and Beaver Creek, in the northeastern part of the plateau, have the writers observed specific evidence of an erosional unconformity, the locality, however, being the only one where the contact is exposed for a considerable distance. Apparently the fine-grained rocks of the Blackhawk and Star Point formations represent a protracted period of fairly quiet sedimentation in which no breaks suggestive of disturbances have been noted. The abrupt introduction of grits and conglomerates in the Castlegate sandstone indicate increased carrying power of the streams sweeping out over the broad flats where the sediments were being deposited. This increased carrying power, it seems likely, was due to increased gradients, due in turn to a definite orogenic movement whose extent is indicated by the wide area in which the conglomerates are found.

The area now occupied by the lower Colorado Plateaus, most of the Uinta Basin, and the eastern parts of the High Plateaus was orogenically inactive during all of the periods of movement after the close of the Paleozoic. We must therefore look elsewhere than in this inactive area for diastrophic evidence by which to assist in correlating events in the Wasatch Plateau. The regions to the south and north offer little aid at present; those to the east afford some interesting parallels. In the region near Meeker, Colorado, on the south limb of Axial Basin anticline, the Mancos shale is succeeded by a thick series of beds assigned to the Mesaverde, and that by an unconformable series, called post-"Laramie," and that in turn by unconformable Wasatch. This sequence suggests that the unconformable post-"Laramie" beds are equivalent to those here called Price River formation—a suggestion strengthened by lithologic resemblance—and that the local geologic histories are nearly identical. The area near Grand Mesa, Colorado, likewise presents similarities. Here the Mancos shale is succeeded by lower Mesaverde, over which come apparently unconformable upper Mesaverde, and then unconformable Tertiary deposits.

The paleontologic data available, however, shed some light on the problem. The fossils of the Price River formation include highly sculptured species of *Unio*, such as *Unio letsoni*, *U. holmesianus*, and other freshwater types, such as *Campeloma*, *Sphaerium planum*, *Goniobasis subtortuosa*, associated with a few specimens of the brackish water forms, *Corbicula occidentalis*, *Modiola regularis*, and probably *Ostrea* sp. These brackish water species seem to preclude a correlation with rocks as young as the post-"Laramie." The highest known marine or brackish water beds in the entire Rocky Mountain and Great Plains regions, except the area containing the Cannonball marine member of the Lance, are only a

little younger than Fox Hills. At many places the youngest marine or brackish water beds are even older than Fox Hills. There is no known source for the brackish water fossils of the Price River beds except extensions of the Cretaceous sea. The particular types do not justify the assumption that they became inured to fresh water and lived in the region long after the withdrawal of salt waters, for all of their relatives give evidence that they required salt water. The only possible explanation of a persistence of these forms later than Fox Hills time would be the assumption that relic seas existed in which brackish water was long enough present to permit their growth. How such seas would bridge the gap necessary between the Price River and Blackhawk formations, if the Price River were Fort Union in age, is difficult to imagine.

The fossils thus far found in the Price River formation agree most closely with those from the Fruitland and Kirtland formations of the San Juan Basin, and this similarity, together with the facts above discussed, leads the writers to believe that the formations are of very nearly the same age. This is probably true also for the upper Mesaverde of Grand Mesa. It should be noted that most of the Price River species occur also in the Laramie formation of the Denver Basin and in the Lance formation of Wyoming, Montana, and the Dakotas. At the present time the relations of Fruitland, Laramie, and Lance are in dispute, though many geologists believe that they do not differ greatly in age. Whatever may eventually be accepted as the correct interpretation, a correlation of Price River with Fruitland places the Price River formation at a time somewhat later than typical Mesaverde and typical Lewis. The true Mesaverde is probably represented by the Star Point sandstone, and part or all of the Blackhawk formation and, according to the interpretation here given, the Lewis is either represented by the upper part of the Blackhawk or by an erosion interval between the Blackhawk and the Price River.

The evidence now available therefore leaves the question of unconformity between the two formations somewhat unsettled, especially in view of the fact that in such beds unconformities are apt to be local and of little importance, as measured in geologic time. However, the writers believe the persistence of the lithologic change and the local evidence of unconformity agree with a difference in fauna, and that the presence between the Blackhawk and Price River formations of a hiatus of importance in the regional history is indicated.

'As has been suggested above, the features of the Mesaverde group in the Wasatch Plateau are doubtless repeated in eastern Utah and much of western Colorado in the succession there called Mesaverde. The writers believe that this group embodies sediments of much the same age, at least

from the Wasatch Plateau to the Grand Mesa, and probably also to northwestern Colorado, excepting the Yampa coal field, where the presence of an overlying marine shale clarifies the stratigraphic succession. Precisely how much of the upper part of the Mesaverde in eastern Utah represents the Price River formation is, for lack of detailed work, not known, but the senior author has traced the Castlegate sandstone as far east as Green River and has delimited the Price River formation in the Horse Canyon district, in the Book Cliffs about midway between the Wasatch Plateau and Green River. Southeast of the Book Cliffs, in the Grand Mesa, it is likely that the upper part of the succession called Mesaverde (Paonia shale member and undifferentiated Mesaverde) is equivalent to the Price River.

Tertiary Formations

Wasatch formation

The Wasatch formation, as recognized in the Wasatch Plateau, consists of three members—a lower member of sandstone, varicolored shale, conglomerate, and small amounts of fresh-water limestone; a middle member of fresh-water limestone, here called the Flagstaff limestone member; and an upper member of varicolored shale and sandstone. Geologists who in past years have examined this general region in reconnaissance have repeatedly emphasized the great variability of the Wasatch formation, stating that hardly any two sections of the rocks, even if taken not far from one another, are alike. The formation does vary much in detail, but the three larger units here defined appear to be consistent throughout the Wasatch Plateau, and the writers believe they have recognized them in reconnaissance examination of parts of the plateau province west of the Wasatch. East of the Wasatch Plateau, in the Book Cliffs—Uinta Basin region—the three divisions of the formation lose their distinctness through the wedging out, in many tongues, of the Flagstaff limestone, and the Wasatch rocks are fairly uniform in composition from bottom to top.

The lower member of the formation in the Wasatch Plateau consists normally of the kind of red, purplish, and gray shale and sandstone that is common throughout the Colorado Plateau; it varies considerably from place to place, here containing much sandstone and there containing mainly shale, and at a few places containing much fresh-water limestone. At many places there is a basal limestone conglomerate. In spite of its variability, its identity in the large seems to be well fixed. The thickness is from 1,200 to 2,000 feet.

The Flagstaff member, named from Flagstaff Peak, in the southern part of the Wasatch Plateau, consists chiefly of fresh-water limestone,

the great thickness of this interesting rock presenting a unique feature of the Wasatch formation. In the southern part of the plateau it attains 1,000 feet, but it thins northward and eastward and is not recognizable in the Book Cliffs. The limestone is largely of a dense, fine-grained variety, cream to tan in color, for which no origin other than chemical or bacterial precipitation seems possible. Blue-gray limestone, filled with casts of fresh-water gastropods and pelecypods, is also abundant. Other limestone beds in the member are made up almost exclusively of the tests of fresh-water ostracods. As a whole, and particularly in those places where the thickness of uninterrupted limestone reaches 800 to 1,000 feet, it is a most unusual and interesting body of rock.

In addition to the limestone, which greatly predominates in the Wasatch Plateau, the member contains at places many beds of dense, white material that seems to be an altered volcanic ash, though detailed examination leaves its origin somewhat in doubt. C. S. Ross, who at the request of the writers has examined it petrographically, states that ". . . the composition is about that of rhyolitic material, but a very detailed microscopic study shows no trace of volcanic ash structure. . . . It is practically structureless and gives no conclusive evidence of any method of origin." Blackwelder[14] has found, in rocks of the Wasatch Mountains that are doubtless equivalent to the Wasatch formation, similar material which he considers certainly to be volcanic ash. It seems likely that the material from the Flagstaff limestone, uncertain though it appears under the microscope, is also volcanic ash. The location of Eocene volcanoes from which this matter may have been ejected is yet unknown, but it seems possible that the vents supplying it may have been just south of the present Wasatch Plateau, in the part of the High Plateaus which received, later in Tertiary time, vast outpourings of lava. This, however, is pure speculation and is founded on negative rather than positive evidence.

The upper member of the Wasatch formation, about 1,000 feet thick, consists largely of varicolored shale and thin beds of fresh-water limestone, with some sandstone, and, in the northern part of the field, occasional veins of ozokerite.[15] This member has been eroded completely from all parts of the Wasatch Plateau seen by the writers, though it is present along the base of the monocline on the west flank and in the broad valley followed by the Denver and Rio Grande Western Railroad at the northern margin of the plateau, transition ground between the plateau and surrounding regions. At the northern end of the plateau,

[14] Eliot Blackwelder: Personal communication.

[15] H. M. Robinson: Ozokerite in central Utah. U. S. Geol. Survey Bull. 641, 1916, pp. 1-16.

north and northeast of Soldier Summit, the contact between the Wasatch and Green River formations seems, on distant view, to present an intertonguing relation similar to that described by Sears and Bradley[16] for northwestern Colorado.

BOUNDARY BETWEEN CRETACEOUS AND EOCENE

The Tertiary rocks of this region, which embody in places as much as 6,000 feet of strata, have hitherto been identified entirely on the basis of lithologic similarity with the Wasatch and Green River formations of northern Utah and southern Wyoming and as a whole are sufficiently different from the underlying Cretaceous to justify the separation. The exact location of the basal boundary of the Tertiary rocks, however, has at many places presented difficulties, though where post-Price River movement affected the earlier beds the unconformity is very clear.

In the Wasatch Plateau the base of the Eocene rocks is at many places marked by a conglomerate, the pebbles of which are largely of fresh-water limestone of the types regionally peculiar to the Wasatch and Green River formations and which may record the reworking of Tertiary limestone beds. Limestone beds in the Upper Jurassic formations of the region west of the plateau might have yielded the pebbles of the conglomerate, but fresh-water limestone is not known in the Jurassic in sufficient quantities to account for the amounts of conglomerate that have been noted. It does, however, exist in the beds of Morrison age of the general region—a more likely source than the older rocks. Regardless of whether the limestone is Jurassic or Tertiary, the conglomerate marks in the plateau the break represented by the angular discordance on the western margin of the plateau—a record of the most important movement shown by the sediments of the region.

There were probably mountains rising on the west which yielded the detrital sediments of the present Wasatch formation. Whether this movement was contemporaneous with the major movement of this general time elsewhere in the Cordilleran province remains to be proved. First judgment would place it thus; but the discovery on the top of the northern part of the plateau, in rocks belonging to the formation here called Wasatch, of invertebrate fossils hitherto known only from the Fort Union somewhat confuses the issue. These fossils, which include such species as *Viviparus trochiformis, Goniobasis tenuicarinata, Columna* (?) *teres,* and *Bulinus longiusculus,* suggest strongly that part of the Wasatch formation of this region may be of Fort Union age rather than typical

[16] J. D. Sears and W. H. Bradley: Relations of the Wasatch and Green River formations in northwestern Colorado and southern Wyoming. U. S. Geological Survey Prof. Paper 132-F, 1924.

Wasatch, and that the main orogenic movement accordingly may not be contemporaneous with the main movement in regions farther east and north, supposedly intervening between Fort Union and Wasatch. The settlement of this question must depend on work on the top and along the west side of the plateau more extensive than that possible during the present study.

No vertebrate remains have thus far been found in the Wasatch formation of this region. Other fossils include species of *Unio, Physa, Helix,* and *Viviparus* that have been considered to characterize the true Wasatch, or at least beds later than Fort Union.

GREEN RIVER FORMATION AND LATER BEDS

The Green River formation is the youngest formation of the region immediately surrounding the Wasatch Plateau. No rocks believed definitely assignable to the Green River formation have been found on the plateau proper, but the formation is typically present in the highlands just north of the plateau, at the western end of the Uinta Basin, where it consists of the usual succession of light-colored shale, sandstone, thin-bedded limestone, and oil shale. The "Manti beds" of Sanpete Valley, named by Cope[17] and examined in reconnaissance by the writers, are believed to represent the Green River formation there. These beds are somewhat different from the usual Green River, in that they consist in places almost entirely of oolitic limestone. Whether or not rocks equivalent in age to the Bridger, Browns Park, and other later Tertiary formations of the Uinta Basin and Wyoming ever existed in the Wasatch Plateau is not known. The "Manti beds" are the youngest rocks, excepting the alluvial deposits, in Sanpete Valley.

SUMMARY OF GEOLOGIC HISTORY

At the beginning of the Upper Cretaceous the region now occupied by the Wasatch Plateau was invaded by the Mancos Sea, whose western shores probably extended in a northeasterly direction not far west of the present plateau. Several local retrogressions of the sea left their records in the littoral sandstone members of the Mancos, and that during which the Ferron sandstone was laid down extended far enough east and lasted long enough to permit the existence in and near the Wasatch Plateau of continental conditions, as testified by the formation of coal beds. East of Castle Valley the passage from Colorado time to Montana time was recorded by uninterrupted deposition of marine shale, but near the plateau the beginning of Montana time was marked by a retrogression similar to

[17] E. D. Cope: The Manti beds of Utah. Amer. Naturalist, vol. 14, 1880, pp. 303-304.

that indicated by the Eagle sandstone in Montana. At any rate, coarser sediments were brought in and the Emery sandstone was laid down.

After Emery time came the final Mancos transgression, short in the southern and western parts of the plateau, but somewhat protracted in the northern part. Throughout the latter part of this transgression the oscillations of the strand became much more frequent, many bands of littoral sandstone were formed in the upper part of the Mancos shale, and finally the deposition of the Mancos closed with the much greater oscillations indicated by the tongues of the Star Point and higher littoral sandstones of the Mesaverde group. The open sea receded for the last time rather early in Montana time, but brackish water conditions recurred sporadically much later. The final withdrawal of the sea left broad flats, on which fine-grained sediments were swept and greatly reworked by sluggish streams and where great coastal marshes and swamps existed. The Blackhawk formation, with its many coal beds, was laid down on these flats. As the sea withdrew farther, conditions became less and less favorable for coal formation, and at the end of Blackhawk time the swamps had practically all disappeared.

After the deposition of the Blackhawk sediments the region was apparently elevated in still more pronounced manner, and planation began in the Wasatch Plateau with contemporary deposition of land and shore sediments now included in the Mesaverde formation in the basins farther east and possibly the Lewis shale in the open sea beyond. Then, after a while, fairly coarse sediments, derived from landmasses near the site of the present High Plateaus, were brought eastward to form the Price River beds of the Wasatch area. East of the Wasatch Plateau there were deposited at this time some of the beds now included in the later Mesaverde of such areas as Grand Mesa, Colorado, where no Lewis shale is recognized, and very likely the so-called Laramie of other areas where a marine shale is identified as Lewis. In San Juan Basin, in southwestern Colorado and adjacent New Mexico, the Fruitland and Kirtland formations apparently record this interval. Deposition of this body of sediments may have continued until latest Cretaceous time, when the Utah region probably rose rather rapidly and was eroded, the products of the erosion contributing to the formation of the post-"Laramie" rocks of Colorado and Wyoming.

During the period of major mountain-making, post-Price River and pre-Wasatch, ranges of Mesozoic and earlier rocks were thrown up on the west, were vigorously eroded, and the products of the erosion were carried widespread over the region to form the present Wasatch formation. With the progress of Wasatch time the crustal movements died down, and the quiescent region was again the scene of broad flats, on which

clastic sediments were deposited, and of temporary lake basins, in which much fresh-water limestone was formed. One of these lakes was unusually large and persistent, and it left the remarkable succession of fresh-water limestones shown by the Flagstaff limestone member of the Wasatch formation. A recurrence of broad flats, to which streams brought clastic sediments from the highlands of Paleozoic and Mesozoic rocks on the west, then gave rise to the upper member of the Wasatch formation. Toward the end of this stage conditions of deposition, as now interpreted, became even less disturbed, and the flats gradually gave place to broad, shallow lakes, in which the evenly bedded Green River rocks were laid down. At this point in the history the sedimentary record of the Wasatch Plateau stops, and the next event of importance recorded in the rocks of the region is the outpouring of vast amounts of lava. The volcanoes nearly all were south of the Wasatch Plateau, but some of the lava from the northernmost vents encroached slightly on the southern margin of the present plateau. At the same time, probably, basic igneous rocks welled up into fissures in the Wasatch Plateau and formed several systems of dikes.

The last, and by far the greatest, uplift of the region, which probably took place late in Tertiary time, brought the body of rocks whose origin has just been summarized into the position they occupy today. In the last stages of this uplift the rocks were broken by normal faults and bent into monoclinal folds by gravitative and tensional stresses. On the west side of the Wasatch Plateau this later folding and faulting is superposed on the earlier, compressional structure with striking effects. The Wasatch Plateau lies in the transition zone between the belts of the Great Basin, where the two structural periods are jointly represented, and the eastern High Plateaus, where the later faulting only is present, and the writers believe that out of a careful study of this transition zone and the eastern edge of the Great Basin may come valuable light on the structural problems of the Great Basin, recently the subject of considerable discussion. The structure as now known suggests strongly the validity of normal faulting as the cause of the prominent features of the Great Basin, but further studies of the region west of the Wasatch Plateau are necessary before valuable discussion of these questions can be attempted.

Discussion

Prof. Charles Schuchert: It is very interesting to study the authors' charts, and especially the colored one that brings out the nature of the environment of the sediments. We see here that the well-known earlier Upper Cretaceous marine formations pass upward into the Mesa-

verde, and that at this time the sea in the west vanishes more and more. Finally, that the upper Laramie and Price River formations are wholly continental ones. Then, in the area studied by the authors, there is a general break in sedimentation that is longer in the west than in the east. If, however, we project their diagram to include areas farther to the east, then there is no break at all between the Laramie and Fort Union. To me this means that we should include all of these formations in the Mesozoic and begin the Cenozoic with the Wasatch, which has the heralding placental mammals of a new era.

Since the time of the very first publications on the Cretaceous-Eocene floras and formations by Newberry and Lesquereux, near the middle of the previous century, there has been a controversy as to where to draw the line between the Mesozoic and Cenozoic of the Great Plains. Gradually this debated question is coming to solution, due to detailed work by the geologists of the United States Geological Survey from Montana south into New Mexico, and it will not be many years more before the rising generation of workers will adjust this matter on the basis of mapping, fossils, and diastrophism.

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CHAGRIN FORMATION OF OHIO[1]

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INTRODUCTION

In northeastern Ohio the Ohio black shale of early reports was divided by Dr. Newberry into the Huron, Erie, and Cleveland shales,[2] of which the Erie was later renamed the Chagrin by Professor Prosser,[3] the entire succession up to the Berea thus becoming:

Berea grit
Bedford shale
Cleveland black shale
Chagrin formation
Huron black shale

in which the type Huron may be largely contemporaneous with the Chagrin[4] and only partly identical with the "Huron" beneath the Chagrin, in the well logs. More recently these strata of northeastern Ohio have been most carefully described by Prosser,[5] whose work furnishes the foundation for the present writing.

[1] Manuscript received by the Secretary of the Society July 11, 1924.
[2] Geol. Surv. Ohio, Rept. Prog. in 1869 (1870), pp. 18-21.
[3] Jour. Geol., vol. 11, pp. 521, 533.
[4] See Ohio Bull. 15 (1912), pp. 515-519.
[5] Charles S. Prosser: Devonian and Mississippian formations of northeastern Ohio. Geol. Surv. Ohio, 4th ser., Bull. 15 (1912).

In northwestern Pennsylvania Dr. I. C. White described the following succession in Erie and Crawford counties, adjacent to Ohio and western New York:[6]

Corry sandstone	Oil Lake group
Cussewago shale	
Cussewago sandstone	
Riceville shale	
Venango group	
Chemung beds	
Girard shale	
Portage beds	

The relations of White's Chemung (Chadakoin), Girard, and Portage (Northeast) to the New York strata have been worked out in the field by the writer and already published.[7] His Venango and Riceville have been combined by Mr. Butts[8] into the Conewango formation, shown to carry fossils in common with the upper Chagrin by Dr. Girty,[9] who has confirmed White's correlation of the Corry sandstone with the Berea grit.[10] Prosser[11] has carried the Chagrin formation and fossils up to the base of the Cussewago sandstone on the Ohio-Pennsylvania line, where the Cleveland shale is absent, while the lowest of the Pennsylvania formations to cross this line into the Ohio Chagrin group is the Girard shale. This makes the visible Chagrin (above the waters of Lake Erie) consist of the Girard, Chadakoin, "Venango," and Riceville, while its under-water portion by implication includes still lower beds (Northeast, etcetera). There is left the ancient problem of the relation of the Cussewago sandstone and shale to the Cleveland, Bedford, and Berea, which will be specially considered presently.

In western New York the established succession[12] is as follows:

(Corry absent)
Knapp beds (conglomerate and shale)
Oswayo shale
Cattaraugus red beds
Chadakoin and subjacent series

[6] Second Geol. Surv. Pa., Q4 (1881).

[7] Bull. Geol. Soc. Amer., vol. 34, p. 69; N. Y. State Museum Bull. 251, pp. 152-154.

[8] U. S. Geol. Surv. Fol. 172. See also Top. and Geol. Surv. Pa., Rept. for 1906-1908, pp. 191, 199, and especially pl. 8. The question of the correlation of White's Venango group with the Venango oil sands, raised in that report, is considered by the writer beyond.

[9] Top. and Geol. Surv. Pa., 1906-1908, p. 191.

[10] Loc. cit.

[11] Ohio Bull. 15, pp. 510-511.

[12] Bull. Geol. Soc. Amer., vol. 34, pp. 68-69; N. Y. State Pal. Rept. for 1902 (Bull. 69), pp. 967-995; N. Y. State Museum Bull. 251, pp. 154-155.

Following down the Allegheny River into Pennsylvania, the Knapp is overlain by the Corry (Berea), a shale wedging in between, and is underlain by the Conewango formation, which is correlated by Butts directly with the Cattaraugus and Oswayo.[13] This leaves open the relation of the Knapp and overlying shale to the Cussewago sandstone and shale, which is discussed beyond. The problems are exhibited by placing the columns parallel, thus:

Berea		Corry	Corry	(absent)
Bedford	?	Cussewago sh. ?	Shale	(absent)
Cleveland	?	Cussewago ss. ?	Knapp	Knapp
Chagrin		Riceville, "Venango"	Conewango	Oswayo, Cattaraugus
		Chadakoin	Chadakoin	Chadakoin
		Girard	etcetera	etcetera

From the above it will be seen that the Chagrin formation is essentially a group, ranging from beds classed as undoubted Upper Devonian into those called "Devono-Carboniferous," or even "Eocarbonic," and it was this that led the writer to undertake its analysis from the wealth of data provided by White and Prosser.[14] This study has been carried through in great detail, and an extensive manuscript, with maps, diagrams, and faunal lists, has been prepared, but only the broader results can be stated here.

The Venango Group

Dr. White's "Venango group" consisted of five members, which, to avoid confusion with the Venango oil sands, we propose to name as follows:

Upper standstone	=	*Woodcock sandstone*
Upper shale	=	*Saegerstown shale*
Middle sandstone	=	*Millers sandstone*
Lower shale	=	*Amity shale*
Lower or Le Bœuf sandstone of White		

It is generally agreed that the Le Bœuf sandstone can be traced into the Panama conglomerate of the adjacent county in New York, which conglomerate lies at or near the base of the Conewango formation. This correlation must be at least approximately correct.

White supposed that his three sandstones were respectively the three oil sands of Venango County on the south, but Butts[15] appears to have demonstrated that the "Venango first oil sand" is the Corry, and that

[13] See references in footnote 8.
[14] Pa. Q4 and Ohio Bull. 15, as previously cited.
[15] Top. and Geol. Surv. Pa., 1906-1908, p. 195 and pl. 8.

the "third sand" is the Salamanca conglomerate midway of the Conewango formation. The "Venango group of oil sands" of the drillers is thus a hybrid thing, and if the name Venango is to have any standing in stratigraphy I contend that it must hold its connotation not from well logs, but from actual exposures, in the sense that White was first to use it, for which a type locality may be found either at Venango Station, Crawford County, or in Venango Township, Erie County. The need for the new names above proposed becomes, however, thus apparent, and they will be used in the analysis of the Chagrin formation, which is now found to consist of the following members:

Riceville shale
Woodcock sandstone
Saegerstown shale
Millers sandstone
Amity shale
Le Bœuf sandstone
Chadakoin beds
Girard shale
(Lower beds concealed)

The Chagrin Formation

On crossing the Ohio State line the eight members just listed are lumped indiscriminately as the Chagrin formation, and in fact if we are to accept Chagrin as a direct substitute for Newberry's "Erie shale" the list will include at base the following underlying strata as far east as Dunkirk, New York:[16]

Northeast shale
Shumla sandstone
Westfield shale
Laona sandstone
Gowanda beds

The rapid loss of sandy sediment in passing west is some excuse for this lumping. Nevertheless, the writer finds that the various members maintain sufficient individuality to be traced with some confidence, even to the Cuyahoga Valley. Throughout this tracing, across Pennsylvania as well as Ohio, the same slow changes in lithology and fossils are evident as in the fieldwork in New York State. The lithic and faunal facies continue to pass diagonally upward across the beds, all of which show a westward thinning.

The strong Le Bœuf sandstone extends, with its characteristic fauna, east and south of Monroe Center (respectively 970 and 920 feet eleva-

[16] Geol. Surv. Ohio, vol. 1 (1873), p. 190; Bull. Geol. Soc. Amer., vol. 34, p. 69; N. Y. State Museum Bull. 251, pp. 150-152.

tion), crossing the Ashtabula River at about 900 feet above tide and Mill Creek northeast of Jefferson at 870 feet and again, at Eaglesville, at 815 feet. The entrance of an abundant *Leiorhynchus* fauna at this point (*L. ohioense* dominating) indicates that the beach sand and fauna have about expired. Crossing the Grand River valley, exposures fail and the Le Bœuf is recognized only as one of the gas sands at Cork, presumably the middle one (805 feet above sea); but since the underlying Chadakoin sediments have meanwhile faded into soft shales of Girard type, the base of the Bradfordian series ("Venango" base) is still marked by lithic contrast and seems clearly to constitute the plane of division between Newberry's upper and lower portions of his Erie shale (Chagrin) on the Chagrin River and west beyond Cleveland "to the lake surface just east of the mouth of Rocky River."[17] The intervening critical points have not been described in print, so far as I could find.

The Chadakoin fauna, here marked by *Leiorhynchus newberryi*, continues in force into Ohio as far west as Kelloggsville, and with some modification to the *Syringothyris* locality north of Jefferson and even to Eaglesville. Its vanishing (*Leiorhynchus*) phase is seen at the Grand River south of Madison and even at Willoughby, both places evidently near its summit.

The Chadakoin base or Girard summit is recognized in the Conneaut Creek cliff two miles east of Kingsville, at about 705 feet above sea, but is not clearly indicated by the literature west of there. Projected, it should come down to Lake Erie at the mouth of the Grand River, where there is a distinct bend in the shoreline.

Returning to higher members of the Chagrin, we find the rich and definitive fauna of the Woodcock-Riceville carrying much farther west than the others, being present in the Cuyahoga Valley from Bedford Glen southward. As sandy layers persist throughout this hundred-foot interval, it is not always easy to distinguish the two members for purposes of mapping. Outcrops near the Woodcock base occur in the northern part of Richmond Township at 1,025 and 1,030 feet above tide, whence the line passes northwest of Leon and south in the Pymatuning Valley nearly to the Wayne town line. The next described localities of these higher faunas are across the Grand River valley at Phelps, Indian, and Crooked creeks, north of which the Woodcock is well defined at 930 feet above tide on Trumbull Creek, where the Riceville has been reduced to less than 50 feet.

Prosser himself linked the Trumbull Creek outcrop with those on both roads two miles north of Thompson and noted the agreement between the fauna here and at Meadville, Pennsylvania (Woodcock-Riceville hori-

[17] Geol. Surv. Ohio, vol. 1 (1873), p. 163.

zons).[18] The Thompson outcrops, being about 980 feet above sea, hold the proper interval above the Le Bœuf sand in the well at Cork, and as they are only 65 feet below the Berea, with at least 45 feet of Cleveland and Bedford between, the Riceville must here be reduced to 20 feet or less.

This fauna appears at Hillhouse and again on Big Creek south of the State road, where it occupies the upper 56 feet of the Chagrin shales and thin sandstones, thus giving room for a greater amount of Riceville, but at the Chardon-Concord road the Woodcock sandstones lie at the very top of the Chagrin formation, next beneath the black Cleveland shale.

This total disappearance of the Riceville shale, 80 feet or more thick in Pennsylvania, is of marked significance. On proceeding west we find the Woodcock similarly cut out of the section between this point and Little Mountain, which accords with the small and diminishing thickness of the entire "Upper Chagrin" (Conewango) between the Chagrin River and Cleveland. But, whereas the higher members are thus eliminated in passing northwestward, they come back into the section as we go southeast up the Cuyahoga Valley. Reappearing first at Bedford (Woodcock horizon), the wedge steadily thickens until at Brandywine Creek and Slipper Run the Riceville also is present with increasing thickness. These relations are shown in figure 1, in which the base of the Bedford shale is made the plane of reference.

The beds between the Le Bœuf and the Woodcock, namely, the Amity shale, Millers sandstone, and Saegerstown shale, are not so highly characterized nor are their outcrops so good. The Millers sandstone is quite fossiliferous on Mill Creek below Dorset at about 940 feet above tide, while the Saegerstown shale carries fossils a mile upstream from there. The outcrops at about 925 feet elevation north of Gould appear to be near the middle of the Amity, the lower beds of which are found at the covered bridge northeast of Jefferson (885 feet above sea) and probably at Eaglesville. Its characteristic fossil, *Leiorhynchus ohioense,* continues west to the Chagrin Valley (Deans Gully) and even to the Cuyahoga.

The fossiliferous beds at Rock Creek village seem to be in the Amity, while the Millers probably comes in at the mouth of Sugar Creek and reappears west of the Grand River valley at Barnes corners, where the overlying Saegerstown, at 900 feet elevation, yields a fauna similar to that near Dorset.

West of this point the fossils of all three of these members fade away into the *Leiorhynchus* facies with an occasional *Lingula,* as is seen in the long section at Deans Gully, Gates Mills, which covers all three divisions, and once more on Sagamore Creek, in the Cuyahoga Valley,

[18] Ohio Bull. 15, pp. 296, 290, respectively.

where the lowest exposure is in the Amity, the higher zone with *Grammysia* is Saegerstown, and the highest fossils are from the Woodcock.

The Amity shale, without fossils, is found in the bluffs at Pleasanton and on Euclid Creek, on Doan Brook at the Case School and below Ambler Boulevard, and at South Brooklyn and Brookside Park. As the Millers sandstone with associated dark shales appears to form the top of the Chagrin, in contact with the Cleveland black shale, at Ambler Boulevard and West Park Cemetery, being then cut out westward by the summit unconformity, the Amity and Le Bœuf alone constitute the "Upper Chagrin" westward from Edgewater Park.

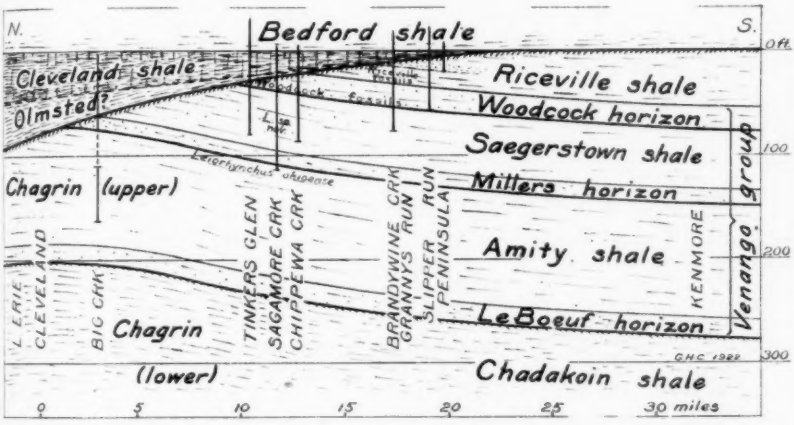

FIGURE 1. *Diagram showing stratigraphic Relations and Unconformity in the Cuyahoga Valley, Ohio, from Lake Erie to Kenmore deep Well*

Vertical lines indicate measured sections reported by Prosser at the localities named under each line.

SUMMIT UNCONFORMITY

The relations just discussed, and partly illustrated in figure 1, seem to mark a great summit erosion of the Chagrin strata at the northwestward. The Riceville, Woodcock, Saegerstown, and Millers divisions, their total thickness over 250 feet in Pennsylvania and still at least 150 feet up the Cuyahoga Valley, each in turn is beveled away and removed from the section. The supposition that these missing members are replaced consecutively by the Cleveland black shale is plausible, but not in accord with (*a*) the irregular discrepancies in combined thicknesses and (*b*) the extension of highly fossiliferous Woodcock and Riceville beds right up to the point where they go under the Cleveland, instead of grading off through Leiorhynchus and Lingula facies and growing darker

and less sandy. The sharp basal contact found by Prosser at base of the Cleveland is, in the writer's experience with true black shales, always evidence of unconformity. It is quite possible, as Prosser asserts, that the Chagrin itself finally passes into dark shales westward from the Cuyahoga, but this is denied by Ulrich (private communication), and in any case these black shales are not Cleveland.

No such marked unconformity has been shown to exist between the Chagrin (Conewango) and the overlying Cussewago sandstone of Pennsylvania, now to be considered.

The Oil Lake Group

White's "Oil Lake group" comprised, in ascending order, the Cussewago sandstone, a barren, massive, and peculiarly incoherent stratum, sometimes with pebbles, the Cussewago shale, and the Corry sandstone. This "group" extends part way into Ohio, being then separated from the Cleveland-Bedford-Berea succession (see preceding tabulations) by intervention of the broad and nearly outcropless Grand River valley. Fossiliferous uppermost Chagrin (Riceville shale) underlies both series, while the identity of the Corry with the Berea is now generally accepted. Published opinion as to the Cussewago sand and shale makes these either (*a*) also Berea, or (*b*) Bedford. White[19] seems to have hesitated between these solutions, while Prosser[20] adopts the former.

This would put the Cussewago shale, consistently about 40 feet or more thick, as the thin shale parting (never over 8 feet and not thickening eastward) in the Berea, while it makes the entire Berea, which has been thinning eastward, jump up suddenly from 40 feet to 75 feet to include the Cussewago. Prosser's solution, moreover, explicitly involves identity of the uppermost Chagrin (Woodcock-Riceville) in Pennsylvania with the Cleveland and Bedford in Ohio,[21] but we have just shown that the Woodcock and Riceville are still present beneath the Cleveland shale west of the Grand River and again in the middle Cuyahoga Valley. The implied continuity of the Bedford and Riceville, also, is not borne out by their faunas.

The other solution is better, but fails to account for disappearance of the Cleveland. No one seems to have made the obvious correlation of the Cleveland with the Cussewago sandstone, which would find support in New York stratigraphy from the rapid eastward passage of the Dunkirk black shale into the buff Canaseraga sandstone. But the Dunkirk thickens and grows sandier to make this transition, whereas the Cleve-

[19] Second Geol. Surv. Pa., Q4, pp. 85-86, 92-94.
[20] Ohio Bull. 15, p. 96; also p. 395.
[21] Loc. cit., pp. 429, 511.

land has nearly vanished at the Grand River valley, nor does it show increase of sand content.

It should be noted here that the lithic similarity of the Cussewago sandstone to the Knapp beds is very marked, and that the writer's correlation of these, which gains strength from the relative positions of the Knapp and Corry at Warren,[22] has not been questioned by critics of his published chart. There is, however, an unconformity between the Knapp and the Corry (Berea).

This unconformity I believe to be the same as that found at the top of the Chagrin in Ohio; so that, just as the Millers and Woodcock sandstones are let into the series in passing east from Cleveland to the Grand River, so in turn the Cussewago sand is inserted in crossing the Grand River valley, to be followed by an increasing thickness of true (non-Bedford) Cussewago shale, which for distinction we will rename the *Hayfield shale* (and limestone).

In this view the shale between the Cussewago sandstone and the Corry (Berea) is at first all Bedford, but the plane of unconformity rises eastward, beveling out the Bedford, as already the Cleveland, and gradually substituting the Hayfield shale in the sections. Some undulations in the plane will account for the erratic behavior of the thin Cussewago (Hayfield) limestone beneath this plane. The shale above the Knapp at Warren probably is Hayfield.

Age of the Bradfordian

Thus, while the beds from far down in the New York Devonian up to the Hayfield show a harmonious succession derived from the east, where each member is either conglomeratic or red, thinning westward into increasingly fine-grained and bluer, then blacker, sediment, with a (somewhat oscillating, but on the whole steady) westward migration of the facies and fauna during Upper Devonian time, the beds above the Chagrin-Hayfield encroach unconformably from the opposite direction, or Mississippi Valley, and hold a different fauna. The red color of the Bedford fades eastward; the Berea-Corry grows finer, more limy and more fossiliferous in that direction. None of these beds, from the Olmsted up, has anything, therefore, to do with the Bradford series (originally proposed for the Cattaraugus-Oswayo-Knapp) characterized by *Cyrtia alta* and *Reticularia prœmatura* in a persistent *Spirifer disjunctus* fauna. The Bradfordian is thus to be admitted above the Chautauquan as the closing member of the eastern Upper Devonian, as dimly foreseen by James Hall.[23]

[22] Top. and Geol. Surv. Pa., 1906-1908, pl. 8.
[23] Pal. of New York, vol. 4, pp. 256-257.

SUMMARY

The Chagrin formation of northeastern Ohio consists at the Pennsylvania boundary of eight recognizable members. It is believed that these can be traced westward to beyond Cleveland, revealing

(1) progressive change to finer and then darker sediments, agreeing with a similar westward gradation in the New York Upper Devonian strata,

(2) faunal changes accompanying the lithic, as in New York,

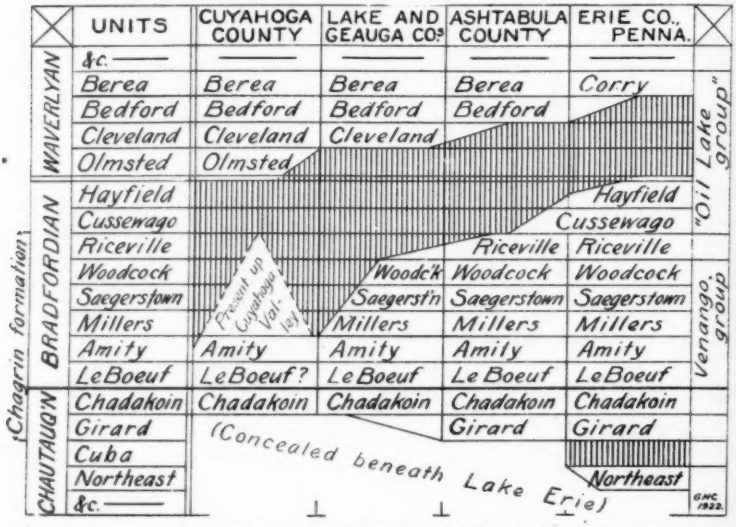

FIGURE 2.—*Correlation of Chagrin and superjacent Beds in Ohio and Pennsylvania*

(3) loss of upper members by summit unconformity in passing northwestward,

(4) progressive eastward overlap of the Mississippian beds (Olmsted, Cleveland, Bedford, Berea) upon these eroded Chagrin strata, and then upon the overlying Cussewago and Hayfield; therefore

(5) the Devonian, though post-Chautauquan, age of the Bradford series, terminating the characteristically upper Devonian *Spirifer disjunctus* fauna.

In any case the Chagrin formation as defined is partly Chautauquan, though mostly Bradfordian in age, and this is probably true even at the type locality. These relations are expressed in figure 2.

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ACTIVE THRUST-FAULTS IN SAN BENITO COUNTY, CALIFORNIA[1]

BY PAUL F. KERR AND HUBERT G. SCHENCK[2]

(Presented in abstract before the Society December 30, 1924)

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[1] Manuscript received by the Secretary of the Society May 6, 1925.
[2] Introduced by Charles P. Berkey.

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Introduction[2]

Our ideas of thrust-faults have been deduced from observations on dislocations in hard, competent strata, such as are found in the Appalachian Mountains of the United States, in the Highlands of Scotland, or in continental Europe, where the epochs of such faulting are commonly either in the Mesozoic or Paleozoic. In the Coast Range of California, however, the writers have recently observed thrust-faulting in incompetent strata of Tertiary and Quaternary age, and in places the pressures responsible for the faulting are still active. In addition, uplifts in soft Pleistocene sediments are causing extensive slumping, and a combination of faults with zones of slumping produce several striking topographic features. These conditions were discovered in San Benito County, about 75 miles south of the city of San Francisco (see figure 1).

San Benito County is crossed by the San Andreas Fault, along which much movement was observed and recorded at the time of the San Francisco earthquake, in 1906. This fault-line is nearly straight and follows a northwest to southeast direction for over 40 miles through the western

[2] The publication of this paper has been made possible through the advice and cooperation of Prof. C. F. Tolman, director of the Stanford summer class in field geology, known as the Stanford Geological Survey. The writers are further indebted to Messrs. Albert Forster and E. E. Maillot, instructors, and to the students in the class for assistance in the field.

Prof. J. F. Kemp, of Columbia University; Mr. F. K. Morris, of the American Museum of Natural History; Prof. J. P. Buwalda, of the University of California, and Prof. Wm. Morris Davis, of Harvard University, have kindly offered constructive criticism during the preparation of the manuscript. It is a pleasure to acknowledge the suggestions of Prof. J. P. Smith, of Stanford University, together with those of Prof. Bruce L. Clark and Mr. Ralph Stewart, of the University of California, in regard to paleontological data. In addition, Messrs. Stock, Furlong, and Elftman, of the University of California, rendered valuable assistance through their identification of the vertebrate remains. Dr. G. Dallas Hanna, of the California Academy of Sciences, aided through an examination of the micro-organisms. Particular thanks are due Mr. C. D. Quaid and other ranchers near Paicines for their interest and hospitality.

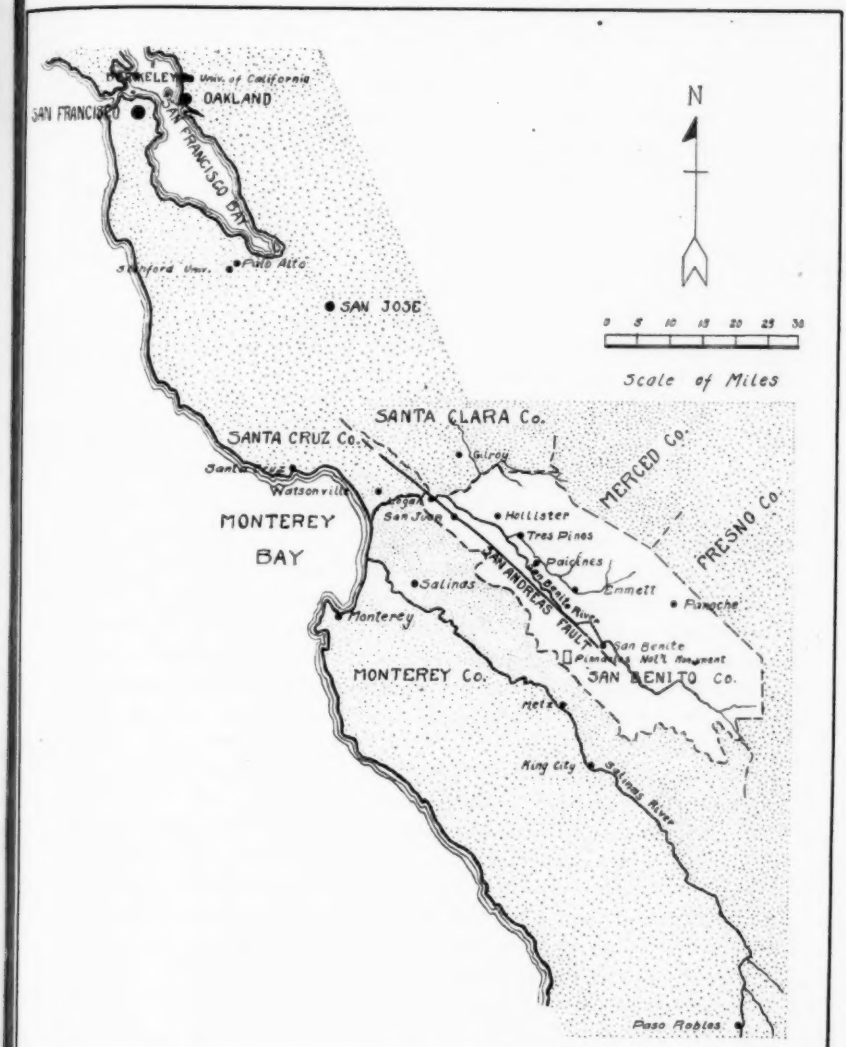

FIGURE 1.—*Location of San Andreas Fault, San Benito County, California*

part of the county. There are a large number of thrust-faults on both sides of the major fault. These thrusts, which are in part active, form pattern which indicates that the movements causing them are part of the general movement along the San Andreas.

The proof of a greater part of the faulting in the region rests upon the identification of horizons in sedimentary formations that are often similar in lithology, but which, according to fossil evidence, differ in age. The problem confronting the geologist is, therefore, one of combined stratigraphy and structure, each dependent upon the other. Consequently, more than usual importance is attached to the stratigraphy, and it is considered worth while to record the stratigraphic features in greater detail than would be otherwise attempted. Since a knowledge of the formations is essential to a proper understanding of the structure, stratigraphy is discussed first.

Stratigraphy

Criteria for correlation

Correlation by means of identity of species proved to be the most reliable method for determining the age of formations in the faulted region under discussion. The dangers of employing, in the field, other methods, such as comparative lithology and structural relations, are apparent when one considers the dynamic history of the region and the fact that similar sedimentary rocks may be formed at different epochs. Examples of the danger of depending upon lithology alone are common. Strata with striking similarity in lithology may be shown, on fossil evidence, to be entirely different in age. Rocks that are hard, compact, and in places brittle may belong to the Pleistocene, while others that are soft, granular sandstones may be found in the Cretaceous. The Vaqueros sandstone of Miocene age is almost identical in appearance with Tres Pinos sandstone of possible Eocene age. We believe that the necessity of securing adequate fossil evidence in the determination of horizons can not be overemphasized, and that correlation should not be attempted on lithologic evidence alone, unless the data presented are striking and characteristic.

In early work in this area, the presence of Pleistocene was overlooked because of the scarcity of fossils. The gravels of Pleistocene age in the region were called Pliocene by Whitney, and so accepted by Lawson, who writes:[4]

[4] A. C. Lawson: The post-Pliocene diastrophism of the coast of southern California. Univ. of Calif. Publ., Bull. of the Dept. of Geology, vol. 1, no. 4, 1893, p. 152.

"The Pliocene age is established by their unconformable relation to the upturned Miocene of Pajaro Canyon, and by the fact that they contain pebbles of the white siliceous shale which characterized the Miocene of the coast. These gravels are exposed in the San Benito, the Tres Pinos, and Los Meritos in a series of very remarkable cliffs." . . .

Pliocene strata are found in the vicinity of Pajaro Canyon, as stated, but the gravels he mentions in the San Benito and confluent creeks are not Pliocene, since they rest unconformably upon marine Pliocene, often contain marine Pliocene boulders, and carry characteristic Pleistocene vertebrate fossils.

These samples are given to show that in this badly faulted region one is not justified in an age assignment unless one encounters quite characteristic lithology (as in the Franciscan Series) or has collected diagnostic fossils. Fortunately, such fossils were discovered in practically all the formations recognized in the field. Some of the more important forms are listed herein.

STRATIGRAPHIC DIVISIONS NEAR SAN JUAN BAUTISTA

General statement.—Figure 2 represents a tentative stratigraphic column of the region studied, while the areal extent of the various formations is shown in figure 3. The column appears as a unit, but the distribution of the formations is such that the discussion of stratigraphy will be divided into two parts: 1. Stratigraphy west of the San Andreas Fault; 2. Stratigraphy east of the San Andreas Fault.

West of the fault one finds a large granite batholith capped in places with remnants of metamorphosed limestone, quartzite, and schist, the series known as the Santa Lucia. The northern edge of this batholith is covered by Tertiary sedimentary and volcanic rocks. The Tertiary sedimentary rocks include Oligocene, Miocene, and Pliocene sandstones and conglomerates, while the volcanic rocks represent rhyolite, andesite, and basalt flows of Miocene age.

East of the fault the basement rock is the Franciscan Series of metamorphosed sediments, serpentine and schist. Adjacent to the fault-line and separating it from the large mass of exposed Franciscan are Cretaceous, Eocene, Miocene, Pliocene, and Pleistocene sediments.

Santa Lucia Series.—A granitic batholith makes up the main portion of the Gabilan Range. This granite is intruded into rocks that are today crystalline limestone, quartzite, and mica schist. It might be designated as the Santa Lucia granite and is possibly the same as that so named and

STRATIGRAPHIC COLUMN OF THE SAN BENITO REGION

SYSTEM	SERIES		FORMATION	SECTION	THICKNESS	DESCRIPTION
QUATERNARY	RECENT		ALLUVIUM		100'±	Alluvium - Soil, sand and gravel.
	PLEISTOCENE		SAN BENITO		1000'±	San Benito - Yellow loosely consolidated sandstone. Blue shale. Blue, red and gray bedded gravel. Indurated sandstone in places. Strata often brilliantly colored. Fossils collected.
TERTIARY	PLIOCENE		PAICINES		800'±	Paicines - Yellow loosely consolidated sandstone. Soft gray sandstone colored by fragments of franciscan metamorphics. Occasional peat seams. Fresh water fossils.
			ETCHEGOIN		1500'±	Etchegoin - Chiefly a yellow sandstone with intercalated shale and conglomerate in places. Massive exposures of buff sandstone with brown "cannon-ball" like nodules common. Contains dendraster reefs.
	MIOCENE	UPPER	SANTA MARGARITA		800'±	Santa Margarita - Coarse mottled sandstone containing large oysters and bryzoa reefs. Massive gray quartzite sandstone with interbedded conglomerate. Argillaceous brown shale.
		LOWER	MONTEREY SERIES: TEMBLOR		400'±	Monterey - Interbedded diatomaceous shale and coarse arkose sandstone. Basal member a poorly sorted breccia with granite boulders.
			MONTEREY SERIES: RED BEDS		200'	Vaqueros - (Red beds) Brilliantly colored red and blue breccia. Crystalline limestone, granitic and volcanic boulders. Clay and gravel beds. (Volcanics) Rhyolite, andesite and basalt flows. (Marine phase) Calcareous coarse yellow sandstone.
			MONTEREY SERIES: VOLCANICS		150'±	
			MONTEREY SERIES: VAQUEROS		150'	
	OLIGOCENE		SAN LORENZO SERIES: PINECATE		1000'±	Pinecate - Chiefly massive yellowish pebbly sandstone with interbedded conglomerate. Cross-bedding common. Fossils rare, but when found indicate marine origin. Line between Vaqueros and Pinecate and between Bautista and Pinecate difficult to draw.
			SAN LORENZO SERIES: SAN JUAN BAUTISTA		1500'±	San Juan Bautista - Most characteristic fossils occur in blue, indurated, calcareous sandstone. Also fine-grained argillaceous, buff sandstone, carbonaceous grit, and clay shale.
	EOCENE		TEJON? TRES PINOS		900'±	Tres Pinos - Massive, coarse-grained, quartzose, buff marine sandstone with conglomerate phases, jointed, more indurated on exposed surfaces. Large erosional cavities common. Forms conspicuous outcrops.
			MEGANOS		1000'±	Meganos - Typical Meganos fossils found in very hard, blue calcareous conglomerate, underlain by jointed, clayey, sandstone with poorly preserved fossils. Foraminiferal clay shale and intercalated hard calcareous shale, may be Meganos. Marine.
	CRETACEOUS (UNDIFFERENTIATED)		CHICO		3000'±	Chico - Interbedded marine sandstone and shale characterized by abundance of mica, carbonaceous material along parting planes, presence of Franciscan pebbles, concretionary sandstone. Chico fossils in hard bluish, calcareous shale. Line between Chico and Knoxville difficult to draw.
			KNOXVILLE		?	Knoxville - Medium-grained, gray, indurated sandstone and hard calcareous shale.
PRE-CRETACEOUS	JURASSIC?		FRANCISCAN		5000'±	Franciscan - Complex series of schist, chert, serpentine, indurated gray sandstone, paper shale and slate.
			SANTA LUCIA	Sl / Am	5000'±	Anzar - A metamorphic phase probably produced by serpentinization of the basic phase of the igneous intrusion.
						Santa Lucia - Crystalline limestone, mica schist and quartzite intruded by granite and alaskite. Diorite and granite rich in hornblende also observed. Pegmatite, aplite and diabase dikes common.

FIGURE 2.—*Stratigraphic Column of the San Benito Region*

described by Lawson.[5] Due to the lack of detailed information, these rocks are included in one series, called the Santa Lucia Series,[6] the age of which is unsatisfactorily determined. The degree of metamorphism has induced some stratigraphers to call these rocks Paleozoic. In this connection J. P. Smith remarks:[7]

"No definite fossils are known in the series, but round crinoid stems are said to have been found in the Gavilan limestones of Fremont's Peak. They are certainly pregranitic, and the granite of the Santa Lucia range is older than the Franciscan. They may be altered Paleozoics, but Hershey thinks they are pre-Cambrian. The rocks are thoroughly metamorphosed and look as old as the pre-Cambrian rocks of southern California."

Lacking more specific data as to the age of the metamorphic rocks, the series is here provisionally designated as Paleozoic. The granite is younger than the sedimentary rocks of the Santa Lucia Series and is pre-Franciscan.

There is a small area of red chert and granite associated with schist and gneiss west of the San Andreas Fault in the vicinity of Anzar Lake. The chert appears to be Franciscan and the serpentinized schist and gneiss an alteration of the granite; all are now confused in their relations because of faulting. In the accompanying stratigraphic column they are included as the Anzar phase of the Santa Lucia Series. Further study might show that the rocks of this limited region are either (1) entirely Franciscan, (2) a slight variation of the Santa Lucia, or (3) a separate series.

Oligocene definitely established.—The oldest sedimentary formation occurring on the west side of the fault is Oligocene in age.[8] Numerous Oligocene fossils have been collected in the vicinity of San Juan Bautista from a formation called, for field purposes, the "San Juan Bautista Formation." The base of this formation is not exposed.

Some of the fossils which establish the age and marine origin of the San Juan Bautista Formation are: *Agasoma graridum* (Gabb), *Fusinus*

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[5] A. C. Lawson: The geology of Carmelo Bay. Bull. Dept. Geol. Univ. of Calif., vol. 1, 1893, p. 6.

A question of nomenclature might be noted. Parker Trask, in an unpublished thesis on "The geology of the Point of Sur Quadrangle, California" (University of California, 1923), maintains that the name Santa Lucia should not be applied to the metamorphics, as it had previously been used to designate the granite, and so calls the metamorphic series the "Sur Series," retaining the name "Santa Lucia" for the granite only.

[6] Named by Bailey Willis. Science, vol. 2, 1900, p. 221.

[7] California State Mining Bureau Bulletin, No. 72, 1916, p. 26.

[8] Credit for the first recognition of Lower Oligocene fossils here belongs to Dr. F. P. Vickerey, of the Southern Branch of the University of California and former paleontologist for the Stanford Geological Survey.

chehalisensis Weaver, *Acila mula* Clark, *Epitonium condoni* Dall, and *Modiolus kirkerensis* Clark.

The Pinecate Formation is stratigraphically above the San Juan Formation. Typical exposures of this second Oligocene Formation occur at Pinecate Peak, four miles northwest of San Juan, and also near the San Juan Cement Works. This sandstone is massive, conglomeratic, often cross-bedded, quartzose, and buff colored, with very few fossils, indicating less favorable conditions for life than prevailed during the deposition of the older sandstone. As far as can be determined, the Pinecate Formation lies disconformably upon the San Juan Bautista Formation, as shown by a study of the section exposed on the west side of Cement Works Hill,[9] where pebbly Pinecate sandstone overlies the yellow Modiolus-bearing sandstone of the San Juan Bautista Formation.

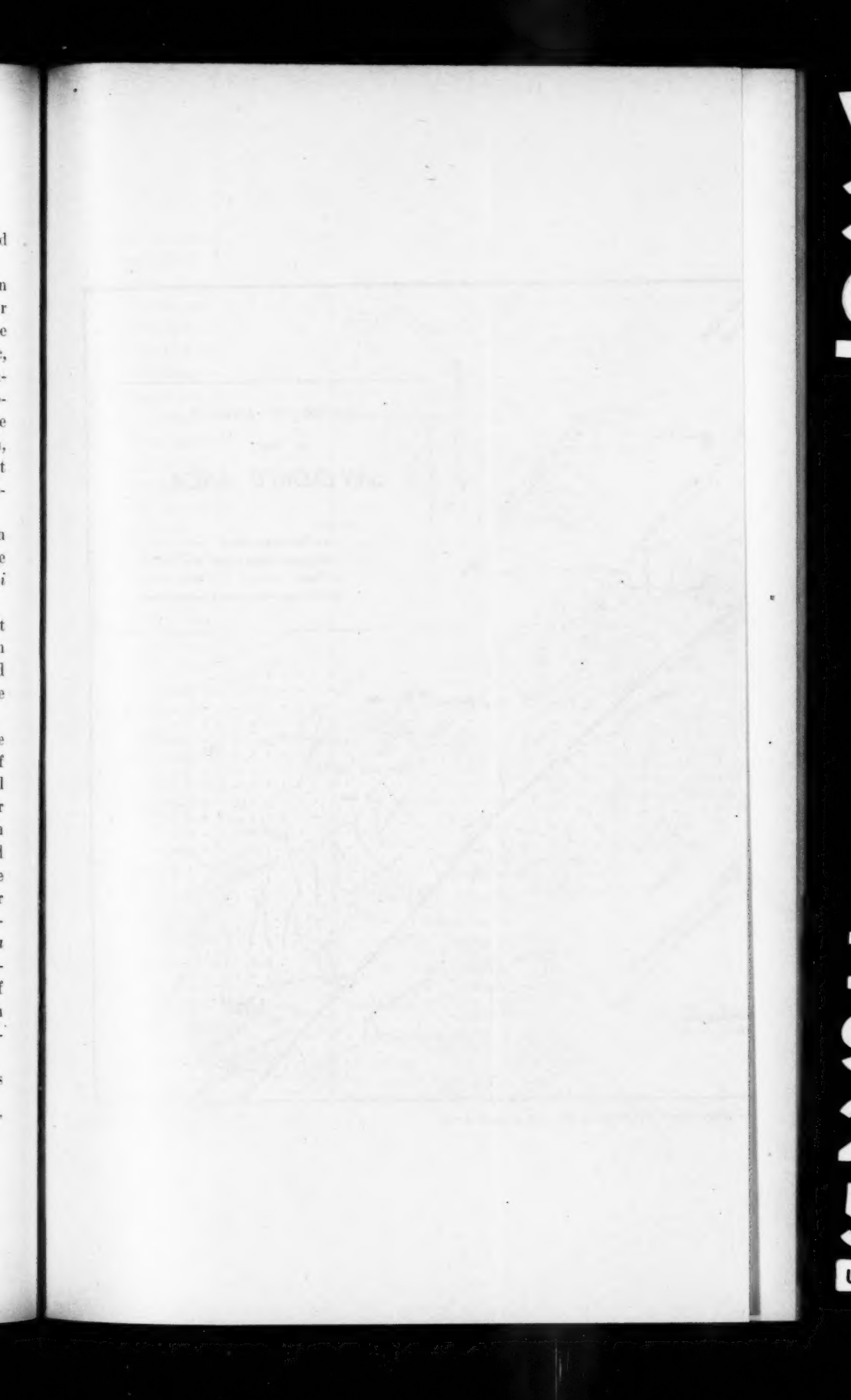
Fossils thought to be limited to the Upper Oligocene were collected in one locality from the Pinecate Formation. These are chiefly the large *Spisula muliniaformis* Wagner and Schilling and *Antigona mathewsoni* Gabb.

No exact correlatives of these two Oligocene formations are known at present, but there seems to be a close relationship between the San Juan Bautista and the San Emigdio formations and between the Pinecate and the Pleito formations, in California. Local formational names must be employed until more definite correlations can be established.

Marine, continental, and volcanic phases in the Miocene.—The Miocene west of the San Andreas Fault comprises beds of marine sandstone of Vaqueros (Lower Miocene) age, so-called "Red Beds" of continental origin, and lavas that are younger than the marine sandstone. Whether a disconformity or unconformity separates the Pinecate sandstone from the Vaqueros is an unsolved problem, but there is a difference in the fossil content of the two formations; for example, the gigantic oysters of the Vaqueros do not occur in the Oligocene. Typical Vaqueros fossils occur in two types of rock: *Turritella inezana* Conrad in a calcareous, medium-grained sandstone, whereas the richest fauna, consisting of *Tivela inezana* Conrad, *Ostrea* cf. *titan* Conrad, and other mollusks, occurs in a conglomerate made up of angular to subrounded pebbles and boulders of granite, limestone, and schist in a buff sandy matrix. Another common Vaqueros sandstone is a gray, crumbly rock with the texture of granulated sugar.

Another Lower Miocene Formation is non-marine in origin. This

[9] Much detailed work will be required to establish unconformities in such a region, where thrusting has often been approximately parallel to the bedding.



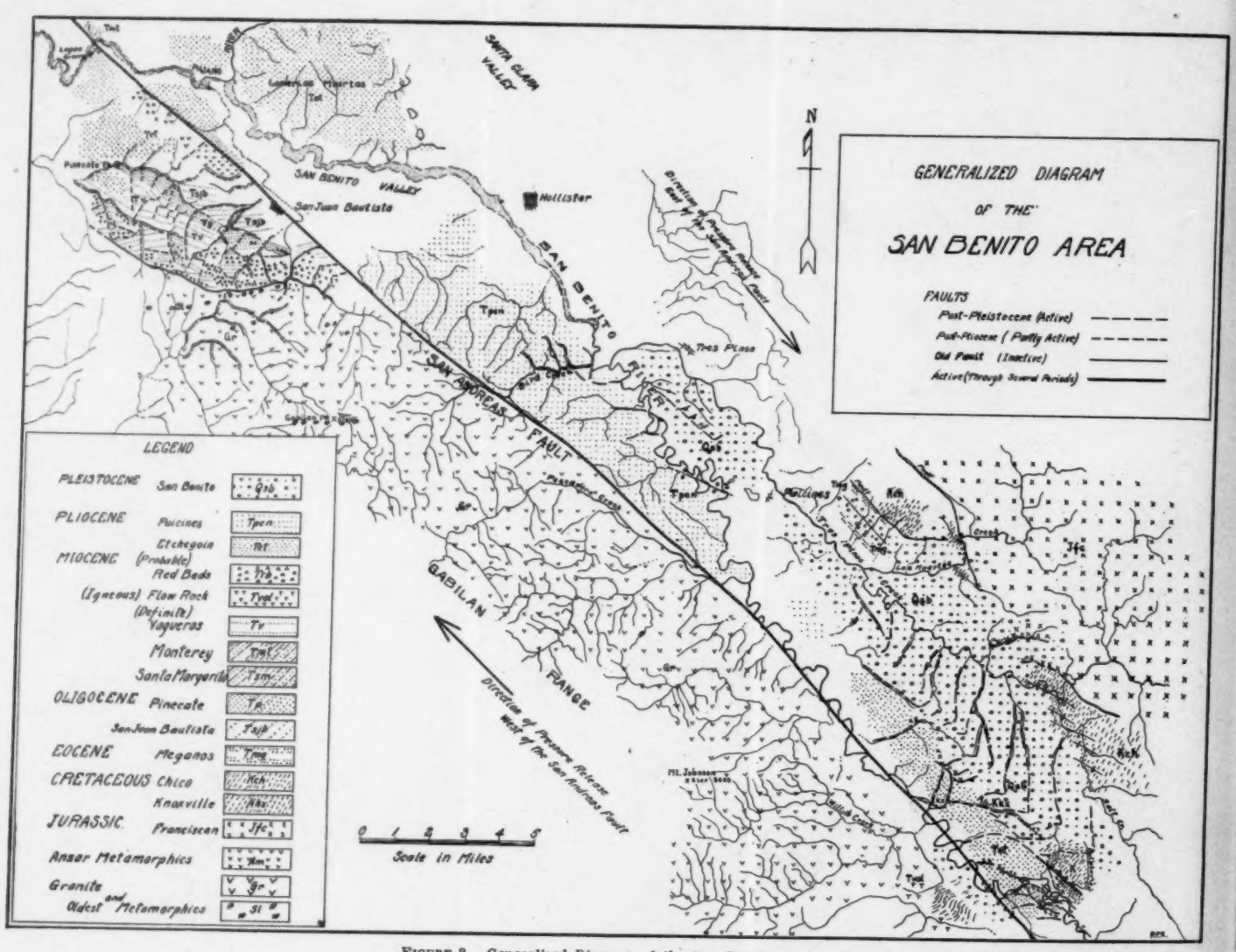


FIGURE 3.—*Generalized Diagram of the San Benito Area*

formation is termed the "Red Beds," characterized, as the name indicates, by a red color. Red Beds generally occur just above the Vaqueros oyster bed, except where faulting has altered the usual sequence. Another distinctive feature of this formation is that the component boulders of angular fragments of granite, crystalline limestone, and schist are sometimes six feet in diameter. The matrix is a red clay and clayey sand. The formation is sometimes cross-bedded, or may have a rude stratification suggesting a conglomerate deposited under torrential conditions in an arid climate, and the distribution of the formation suggests that the Red Beds must have formed a continuous stream channel back to the source of supply, the Gabilan Range.[10] That this is a breccia of continental origin is not doubted, and its Lower Miocene age seems certain, but there are many problems connected with this formation that deserve detailed study.

The flow rocks in the vicinity of San Juan Bautista are rhyolite, andesite, basalt, and agglomerate. These are younger than the Vaqueros sandstone and may be seen overlying that formation. In the cases where the rhyolite rests upon the sandstone directly, there is a zone of silicification and recrystallization of the sandstone along the contact.

Pliocene overlap.—Purisima (Pliocene) marine sandstone, with numerous fossils, masks the older formations in the vicinity of Pajaro River and southward. At Logan Quarry, marine Pliocene lies unconformably upon granite. Elsewhere the same formation covers the Oligocene sedimentary rocks. In other places there are loose gravels and sands, lacking fossils, which can not with any assurance be assigned to the Pliocene; they may be Pleistocene.

MIOCENE OVERLAP NEAR WILLOW CREEK

The work in the Willow Creek area (see southeastern part of figure 3) was of an exploratory nature and little was accomplished besides the identification of the formations. The granite exposed here is a continuation of that studied in the vicinity of San Juan. Monterey Miocene diatomaceous shale and interbedded arkose sandstone is the only marine formation in this area and is best exposed in Bear Valley. The shale is fairly rich in the diatom *Coscinodiscus increfus* A. Schmidt. Other fossils of a fragmentary nature were collected; these are *Arca* sp., an

[10] Professor Tolman reports (verbal communication) that he has seen the same type of beds in the process of formation in the semi-arid regions of Arizona, where occasional torrential rains would flood the bajada regions with mountain débris. He has discussed "Erosion and deposition in the southern Arizona Bolson region" in Jour. Geol., vol. 17, 1909, pp. 136-163.

echinoid, fish bones and scales. These Monterey shales are probably Middle Miocene in age.

The diatomaceous shale and interbedded arkose overlie the granite unconformably. As the San Andreas Fault is approached, the shales are greatly contorted.

Lavas in this vicinity are probably a continuation of the rhyolite that occurs typically in the Pinnacles National Monument, and they lie stratigraphically above the Miocene sediments.

A superficial formation and the youngest one in this small district consists of loose gravel composed chiefly of rewashed granite, together with fragments of diatomaceous shale. The age may be Pleistocene.

STRATIGRAPHY EAST OF THE SAN ANDREAS FAULT

General statement.—East of the San Andreas Fault, Jurassic, Cretaceous, Eocene, Miocene, Pliocene, and Pleistocene formations occur. The San Benito gravels, Pleistocene in age, serve as a stratigraphic key, since they are found in contact with all of the other formations on this side of the fault.

Franciscan metamorphic series.—The series of serpentine, quartzite, chert, schist, shale, graywacke, and metamorphosed sandstone is widespread east of the fault and belongs to the Franciscan Series, so well developed in the Coast Range of California. The series has been placed in the Jurassic by C. H. Davis[11] and others, because the Franciscan has been found to overlie unconformably the Santa Lucia Series and contains Jurassic fossils.[12] Yet it should be noted that *all* of the rocks classed as Franciscan need not necessarily be Jurassic and the lower members may even be of Paleozoic age. The present study throws no light on this problem, since the Franciscan in this region was not found in contact with any older formation, and all contacts except with the Pleistocene were fault contacts.

Cretaceous and Eocene sedimentaries.—The Cretaceous east of the fault may be subdivided into the Knoxville (lower) and the Chico (upper). This separation, in certain localities, is difficult. Knoxville occurs in small blocks east of the San Andreas Fault (southeastern part of figure 3), where they have been brought up by thrusting. This sandstone bears the diagnostic Knoxville fossil, *Aucella crassicollis* Keyserling. In the vicinity of Tres Pinos Creek, Knoxville and Chico were mapped as undifferentiated Cretaceous. Later studies may show that the non-

[11] C. H. Davis: New species from the Santa Lucia Mountains, California, with a discussion of the Jurassic age of the slates at Slate's Springs. Jour. Geol., vol. 21, 1913.
[12] J. P. Smith: Op. cit., p. 32.

concretionary sandstone and shale is Knoxville, while the concretionary sandstone and fossiliferous shales are Chico. The age of the younger Cretaceous rocks is established as Chico by such fossils as *Baculites* sp. and *Pecten* cf. *operculiformis* Gabb.

The next younger formation east of the San Andreas Fault is Eocene, recognized with certainty at one locality, namely, in a denuded anticline two miles east of Paicines. The horizon established is Meganos (Middle Eocene), as proved by abundant fossils, among which are *Cryptochorda* (*Ancilla*) *californica* (Cooper), *Natica hannibali* Dickerson, and *Turbinolia* sp. These fossils were obtained chiefly from the western limb of the anticline in a calcareous conglomerate. Below this conglomerate lies a shaly sandstone which contains poorly preserved corals (*Turbinolia*). This coral-bearing sandstone occurs in both limbs of the anticline.

Overlying the fossiliferous Meganos conglomerate is a massive, buff sandstone which has, to date, yielded no diagnostic fossils. This sandstone is quite similar, lithologically, to the Pinecate sandstone of the San Juan Bautista Region. Should the two formations prove to be the same, it would give valuable information as to the amount of movement that has taken place along the San Andreas Fault. Unfortunatley, proof is lacking, so it is more justifiable, at this time, to consider this massive formation as Tejon (?), because it overlies well established Meganos with no marked unconformity.

Characteristics of the Miocene and Pliocene.—Santa Margarita (Upper Miocene) sandstone, shale, and conglomerate outcrop along San Benito River (southernmost edge of figure 3) east of the fault. Conspicuous ledges composed of *Ostrea titan corrugata* Nomland and a bryozoan reef characterize this formation, which may be separated from the Etchegoin (Pliocene) by an unconformity, although the lithology of the two formations is quite similar and no actual contact was discovered.

Marine Lower Pliocene is established by an abundant fauna from the San Benito area. The formation consists of interbedded sandstone, shale, and conglomerate with a rich littoral fauna, closely related to the Etchegoin of the Coalinga region, but with some Merced Pliocene affinities. Common forms collected are: *Dendraster gibbsi* Remond, *Dendraster ashleyi* Arnold, *Pecten coalingensis* Arnold, *Pecten oweni* Arnold, *Pecten healyi* Arnold, *Schizotherus pajaroanus* Conrad, *Arca trilineata* Conrad, *Macoma nasuta* (Conrad), and *Alectrion morani* Martin. It is likely that more detailed studies of the sediments and faunas will prove that much of the marine Lower Pliocene of California represents one epoch

of deposition, and certainly this region, with its mixture of species supposed to be diagnostic of various Pliocene horizons, is a critical one for such studies.

Continental Pliocene, herein given the local formational name "Paicines" pending more exact correlation, is the principal formation in the vicinity of Bird Creek (near center, figure 3). This formation consists of loosely consolidated sandstone interbedded with shale, which is carbonaceous in many places and in at least one locality contains fresh-water fossils, such as *Anodonta* sp., *Pyrgulopsis vatesiana* (Cooper), ostracods, and fish scales. The sandstone is generally buff or light gray in color and on hillsides weathers easily to a soft, sandy soil that obscures all outcrops. Along stream courses, however, the processes of rock decay have had less time to act and also there is a slight degree of induration due to more abundant moisture during the winter months. Therefore the exposures are more abundant and it is possible to tell something of the structure and stratigraphy by examining these outcrops in the streams. This sandstone of the Paicines Formation is composed mainly of quartz and feldspar, with scatterings of hornblende, mica, chromite, and glaucophane.

The age of the Paicines is, in all probability, Pliocene. The gastropod mentioned is characteristic of the Pliocene[13] and Doctors J. P. Smith and G. D. Hanna, who examined the specimens, are convinced that the formation is Pliocene.

It is practically impossible to separate these Paicines beds from the Pleistocene beds, and all reliable criteria point to about the same thickness of the two formations. At no place could any unconformity, disconformity, or even a definite contact between strata assignable to the two formations be observed. However, since Pleistocene was established by fossil evidence in the Los Muertos area and Pliocene in the Bird Creek area, it is probable that future work will discover an unconformable relation between the two formations.

An unusual thickness of Pleistocene.—Unconformably above marine Pliocene in the San Benito region is a great thickness of non-marine beds, a large part of which is unquestionably Pleistocene, as established by *Equus* near *occidentalis* Leidy and camel remains. The formation is made up principally of loosely consolidated yellow sandstone, blue shale, and red, blue, and gray bedded gravels. The strata are characterized by brilliant coloring. A single exposure of Pleistocene gravels at one

[13] Harold Hannibal: Synopsis of the recent Tertiary fresh-water mollusca of the Californian Province. Proc. Malacological Society, vol. 10, 1912, p. 202.

locality measured 500 feet. Other sections show interbedded sandstone, sandy shale with bog iron, and conglomerate. These Pleistocene gravels were named "San Benito gravels" by Lawson,[14] who thought they were Pliocene in age.

In addition to Pleistocene gravels, there are a number of exposures of old river gravels that truncate the Pleistocene strata and are definitely younger. These are not connected with the present stream channels, but represent a period of erosion following Pleistocene deposition and preceding the uplift which is still in progress. These younger gravels may represent the first stages in the uplift of an old floodplain.

Figure 2 is a summary of this stratigraphic discussion. It will be noted that nearly all of the now-recognized subdivisions of the stratigraphic column of the Coast Range of central California may be studied in the San Benito area. Some of these divisions are for the first time established in this region. The thickness of the formations have been estimated, but such computations are subject to error, due to the extreme faulting which has taken place. With this outline of the stratigraphy in mind, it is now possible to dwell upon the structural features and their topographic expression.

Structural Features and their topographic Expression

General statement

The San Andreas Fault divides the structural features of the region into two parts. West of this line the release of pressure is toward the northwest, while on the east the release[15] is relatively in the opposite direction. The great fault is a major line of weakness, from which radiate minor lines of weakness on either side. The structural relations of the region are those of faulting rather than folding, and a generalized diagram of the fault pattern produced is shown in figure 3. The main features of this pattern should be borne in mind during the remainder of the discussion in order to appreciate the character of the structural phenomena. On the basis of structural features and for convenience in description, the area west of the fault-line is considered separately from that on the east.

[14] Op. cit.

[15] The term release of pressure is used in order to avoid a complicated discussion which would necessarily follow an assignment of directions to forces. The direction of release is evident, while an analysis of the forces is beyond the scope of the present paper.

THE SAN ANDREAS FAULT

Since the portion of the San Andreas Fault within this region plays such an important rôle, a few words should not be out of place concerning the character of the movement generally accredited to it as a result of the studies following the earthquake in 1906 and published in the "Report of the State Earthquake Commission," papers in the Seismological Society of America, and elsewhere.[16]

The main fault-line, together with a large branch, has been traced from the vicinity of San Francisco as far south as San Diego County, a distance of over 500 miles. Several severe earthquakes have occurred along this line in addition to the well known San Francisco earthquake. In general, the fault follows a remarkably straight line, and such displacements as have been observed show that the western side of the fault is moving northwest when considered in relation to the eastern side, which is moving southeast.[17] The main movement appears to be horizontal, as shown by offsets in lines of trees, breaks in fences, and similar evidence. The total horizontal displacement is unknown, but may be as great as twenty miles.[18]

TERTIARY THRUST-BLOCKS WEST OF THE SAN ANDREAS FAULT

The succession of events.—West of the San Andreas Fault, near San Juan Bautista, there are a number of thrust-blocks in competent Tertiary strata. The succession of events responsible for bringing about these features which are observed today follows:

First. Deposition of Oligocene marine strata upon an oldland of granitic and metamorphic rocks; deposition of marine and continental Miocene rocks, an outpouring of lavas, and the deposition of Pliocene marine rocks, the entire column aggregating possibly 4,000 feet.

Second. Uplift with some low folds produced.

Third. Peneplanation by normal processes of erosion.

Fourth. Uplift by thrust-faulting in post-Pliocene time, followed by

[16] H. O. Wood: California earthquake. Bull. Seis. Soc. Am., vol. 6, 1916, pp. 58-160.
B. Willis: A fault map of California. Bull. Seis. Soc. Am., vol. 13, no. 1, 1923, p. 1-12 and accompanying map.
A. C. Lawson: The mobility of the Coast Ranges of California. Bull. Dept. Geol., Univ. of Calif., vol. 12, no. 7, 1921.

[17] The California earthquake of 1906, edited by David Starr Jordan. Robertson Co., 1907, p. 300.
Science Service has published a map giving directions of movements.

[18] Prof. A. C. Lawson, at the annual meeting of the Geological Society of America, December, 1924, stated that recent investigation along the fault in a region south of San Benito County seems to indicate a displacement in the neighborhood of twenty miles.

erosion reducing the region to one of mature topography, with many of the features of block-faulting defaced but not removed.

The faulting in the region is shown in greater detail in figure 4 than appears on the generalized diagram, figure 3. Pressure has been exerted on this area from several different directions. The result of this action has become manifest in the formation of blocks, tilted in part and also subjected to thrusting. The faults which bound the blocks are thrusts. This is shown by the succession of beds illustrated in the section and the presence of fault planes with westerly dips of about 50 degrees. Each block appears to have been thrust upon the one ahead by pressures from the west and south.

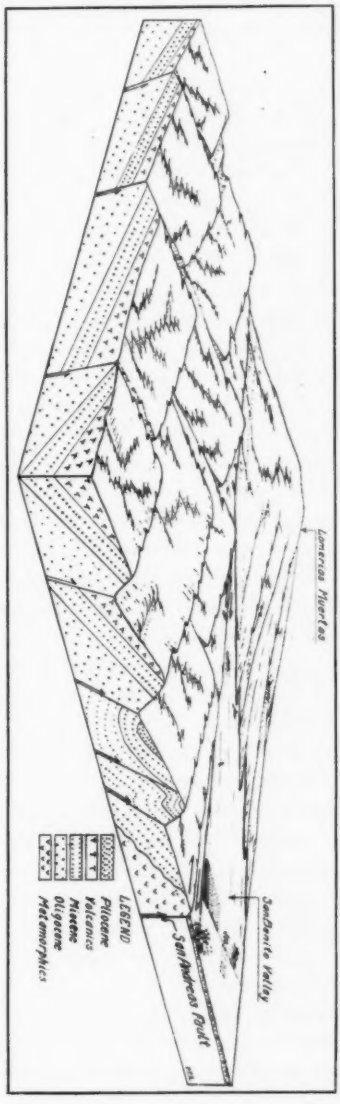


FIGURE 4.—*Thrust-blocks west of the San Andreas Fault*
The location is in the vicinity of San Juan Bautista

Character of movement.— There are many secondary faults, and, as might be expected, the movement on each is not great in comparison with the movement along the San Andreas. It is doubtful if either the vertical or horizontal displacement exceeds 1,000 feet in more than a few places; as a rule, it is considerably less. The general character of the movement is one of small vertical displacements combined with a moderate horizontal displacement.

The block diagram, figure 4, is intended to illustrate not

only the nature of the faulting, but the type of topography produced. It represents a series of blocks each in turn being thrust over the one ahead. The strata are dipping at about the same angle (usually from 20 to 45 degrees in this area) in each block, and the dip of the fault-plane, wherever it can be determined, varies from about 60 to 80 degrees. The blocks have a gentle back slope, which is usually nearly that of the angle of dip, but each block presents a steep declivity on the face, and that side stands out in marked contrast to the back slope. These declivities may well be termed weathered thrust-scarps. The older formations outcrop at the base of the scarps and the most recent at the top Each block along the scarp front rests upon younger strata belonging to the block adjoining and in turn has older strata thrust upon it on the back slope. The formations are offset along the strike between adjacent blocks. Some members are cut off at the edges of the blocks.

This interpretation of the structure is based upon a study of several formations. For instance, the Red Beds furnish a very good structural marker. They extend through the region of blocks for about five miles. These beds are faulted against sandstone of either Oligocene or Vaqueros age. In some instances the old channel in which the Red Beds were deposited has been offset. In other places, however, it is only possible to find a fault-line by tracing the contact between the rich clay soil (which is formed by the surface weathering of the Red Beds) and the yellow sandy soil of the older sedimentary beds.

Oligocene and Miocene strata are badly fractured. In regions of good exposure fault striæ are in evidence. Small fault-lines and unweathered scarps may also be seen in a number of places, and it is possible to trace the fault zones in a few places by means of recent rifts in the soil.

It is possible to show that the San Juan Bautista, the Pinecate, and the Red Beds have all been repeated by faulting, although, as has been pointed out, the beds of Vaqueros age can not with certainty be separated from the Pinecate and San Juan Bautista, except where fossil evidence is at hand. Thus, the determination of the structural features in the sedimentary strata depends largely upon a combination of the observed attitude of the strata, the repetition of beds, as shown by fossil evidence, and the careful tracing of the Red Beds.

Thrust-faults in the volcanic rocks.—In addition to evidence of thrusting obtained by the comparison of adjacent strata of the Tertiary sedimentary formations, there is evidence of thrusting in the Tertiary lava flows and associated clastic rocks. These volcanics usually show well developed flow structure which is often accentuated by weathering. The

normal contact between flow rocks and the underlying sedimentary rocks may be studied in many places, where there will be seen a gradual transition from a soft, poorly cemented sandstone with a high percentage of quartz to a hard, silicified sandstone; then to a quartzite; next, to a glassy rhyolite, and finally to a normal flow rock.

In several parts of this region the flow rocks are found lying between beds of Vaqueros sandstone. One might conclude at first that during Vaqueros time there was an alternation of lava flows and sedimentary deposition. Close observation, however, proves that the sandstone is not continuous along the strike, but is frequently faulted diagonally past the flow rocks, and the flow rocks are in turn faulted past the sandstone. Fault striæ and striated scarps support this interpretation. Such scarps are observed to dip generally toward the west or southwest at an angle of about 60 degrees, and where striæ may be seen the markings indicate both horizontal and vertical components producing a resultant thrust. The faulting, however, is very complex, and in some places a half section is divided into a large number of small thrust-blocks.

The igneous rocks are not intrusives. The areas of silicification of the Vaqueros sandstone by the volcanic rocks always occur beneath the volcanic members. Moreover, in some localities the flows are composed of agglomeratic muds. In general, the structure and texture of the igneous members indicate flows rather than intrusions. The volcanic rocks are confined to the vicinity of the granite contact and, in a very general way, run parallel to it. As previously stated, however, they are interrupted by faulting and are by no means continuous. In some places they extend out into the granite and the same type of faulting continues, while at another place the granite has actually been thrust over rhyolite.

Extension of faulting into the granite.—The granitic mass which forms the backbone of the Gabilan Range is covered in a number of places by quartzite, schist, and crystalline limestone. These metamorphic members, the oldest rocks in the region, intruded, and, metamorphosed by the granite and later largely eroded, have since been faulted and subjected to considerable displacement. Numerous faults in the limestone and schist may be observed along the main ridge just west of Gabilan Peak. The same block topography exists in the granite that one finds in the surrounding stratified rocks underlain by granite. The period of erosion responsible for leveling the back slopes of the blocks shown in figure 4 was also responsible for the erosion of similar slopes in the granite. One concludes from topographic evidence and the presence of extensive faulting in the metamorphic rocks that the thrust-blocks in the

strata adjacent to the granite contact continue out into the batholith for a considerable distance.

Block topography.—The topography shown in the diagram just mentioned is a characteristic feature of the region west of the San Andreas Fault. There is a remarkable similarity between the blocks. Where the granite is exposed on individual blocks it appears along the foot of the weathered scarp. Aside from this fact, the evidence of faulting outside of the limited area within four or five miles west of the San Andreas is only physiographic. In view of the close connection between topography and structural features, where the fault-lines may be determined by means of geologic evidence, it seems that the continuation of this type of topography is at least strikingly suggestive of a continuation of the same type of structure.

The blocks of the region appear to be tilted portions of a coastal plain leveled in late Pliocene or in Pleistocene time. Several former stream channels may be traced by means of gravels deposited in the old river beds. These gravels show in a general way the drainage pattern produced upon the coastal plain both before and during the early stages of the uplift. The channels apparently mark the cycle of erosion which occurred at that time and continued until broken by the uplift and consequent faulting which produced the present topography and drainage pattern. This evidence is introduced in order to eliminate the consideration that the block features may be in part due to different cycles of erosion, since only one cycle besides the present one appears to have occurred since the region was last a coastal plain. The block topography supports the idea of general block faulting.

EAST OF THE GREAT FAULT

East of the San Andreas Fault a sequence of events took place similar to that recorded on the west of the fault, but different strata are represented and the thrust-scarps face in the opposite direction. The history of events leading up to present conditions may be summarized thus:

First. Deposition of marine Cretaceous and Eocene strata on an old floor of Franciscan metamorphic rocks, followed by deposition of marine Miocene, continental and marine Pliocene in restricted areas.

Second. Uplift, folding and faulting throughout the entire region.

Third. Peneplanation by normal erosion and extensive Pleistocene sedimentation in parts of the area.

Fourth. Uplift by thrusting, which is continuing at the present time.

Deposition has not been uniform throughout the area, one section con-

filling marine Pliocene while in another the Pliocene is continental. Eocene appears in only one section and the thickness of the Pleistocene is extremely variable. Therefore the region east of the San Andreas fault will be considered in three divisions: (1) The region of continental Pliocene (with some Pleistocene), Bird Creek; (2) the section of marine Eocene (with Franciscan, Cretaceous, and Pleistocene assuming minor importance), Los Muertos Creek; (3) the main Pleistocene area.

POST-PLEISTOCENE UPLIFT NEAR BIRD CREEK

General statement.—The region east of the San Andreas Fault, in the vicinity of Bird Creek (see figure 3 for location), forms the connecting link between the San Juan area and the region farther south. From a structural standpoint, this region east of the fault may be divided into two parts—that east of San Benito River and that part west of the river. West of the San Benito River is a complicated and broken area in soft Pliocene[19] strata. East of the river is an uplifted block of Pleistocene showing an unusual line of old river terraces and also showing that there has been post-Pliocene diastrophism in this vicinity.

Complex faulting in continental Pliocene beds.—The strata in the part of this area west of the San Benito River have been subjected to considerable movement in post-Pliocene times. Exposures with well defined dips of from 45 to 90 degrees are common along the main channel of the San Benito and also along Bird Creek. Only one definite fold, an asymmetrical anticline, may be traced, and that only for a short distance along the San Benito west of Paicines. Complex faulting in these beds may be seen along Bird Creek and along the main portion of the San Benito River. The solution of the fault pattern for the section is complicated by lack of exposures on the hillsides. Structurally, it is only possible to say at present that the section presents a picture of complex faulting in soft non-marine beds of Pliocene age. These are in close proximity to the San Andreas Fault. The character of the faulting is, for the most part, obscured, but several areas of slumping and cut-off drainage suggest that the same type of movement is taking place here as may be observed in the regions of harder strata soon to be described in areas farther south along the main fault.

[19] As previously stated, these strata are considered to be continental Pliocene in the opinion of paleontologists. Their lithology, however, is very similar to near-by Pleistocene. In view of the scarcity of fossils in the latter formation, the suspicion remains that evidence which would show these beds to be of Pleistocene rather than Pliocene age may have been missed.

Uplifted post-Pleistocene surface.—Proceeding now to the area east of the San Benito River, one finds that the region is underlain by loosely consolidated conglomerate sandstone of Pleistocene age. This formation outcrops along a ridge west of Tres Pinos and on both sides of Tres Pinos Creek farther to the south (see figure 3). These Pleistocene beds are either flat-lying or dip at angles not exceeding 15 degrees. The same beds are discussed below in connection with thrusting, but at this point it is desired to show that in the vicinity of the town of Tres Pinos there is evidence of un uplifted, post-Pleistocene erosion surface.

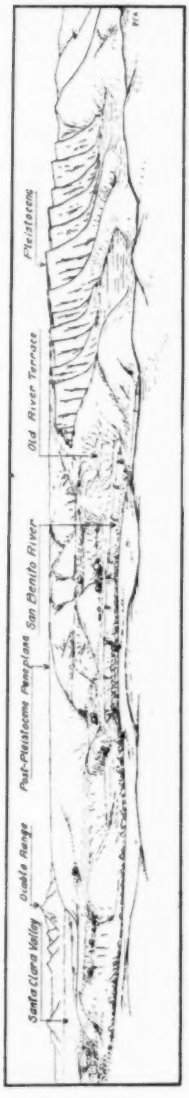


FIGURE 5.—*Uplifted Block of the post-Pliocene Surface between San Benito River and Tres Pinos Creek, east of San Andreas Fault*

Near Tres Pinos a cliff faces the San Benito River. At the foot of the cliff are a number of old river terraces, apparently former river channels (see figure 5). These terraces are warped, as shown by the fact that they still retain the form of meandering stream channels, and yet the old channel floors are no longer flat-lying. There is no evidence of a subsequent erosion cycle, and therefore the warping of the channel bottoms does not appear to be a result of erosion, but is due to tilting. Further evidence of such action is shown in the sculpture of the cliff above the terraces. The erosion is not of the simple dendritic type that one would expect to find in elevated soft strata, but, on the contrary, the cliff is divided into a series of blocks all about 500 feet in height and slightly tilted.

In a region of such pronounced faulting it is reasonable that a cliff of this character would be formed by the uplift of a series of blocks along a fault-line. This series of small blocks is in turn a part of the large block that is represented in figure 5. The top of this block is an old surface carved in the Pleistocene strata which cover the area, and a remnant of the old Santa Clara Valley. Topographically and structurally, this block should

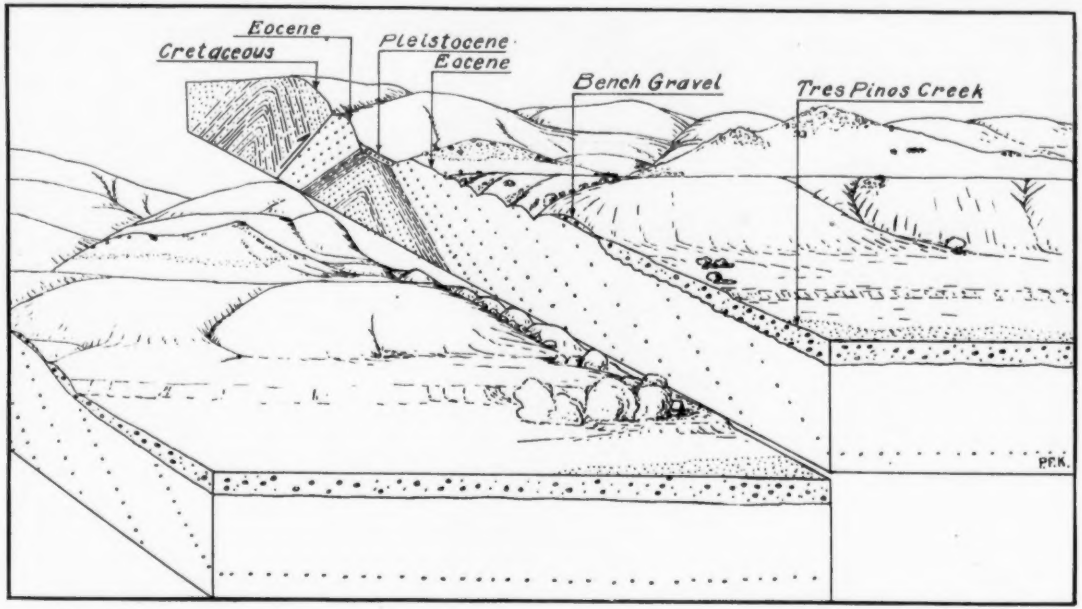


FIGURE 6.—*Section in Cretaceous and Eocene Strata east of San Andreas Fault, near Paicines, Los Muertos Area*

be considered a post-Pleistocene erosion surface that has suffered faulted uplift.

THRUST-FAULTS IN PRE-MIOCENE STRATA

Los Muertos Area.—Southeast of the locality just described and in the vicinity of a branch of Tres Pinos Creek called Los Muertos Creek is a large area of Franciscan, Cretaceous, and Eocene. All three formations are partly overlain by Pleistocene gravels (see figure 3). By a study of these older strata it is possible to determine the structural effect produced in the younger strata by movements in the older mass, and since the following discussion is chiefly concerned with thrusting in soft rocks, it is advisable at this time to bring forward one of the examples of thrusting in the old rocks of the district.

FIGURE 7.—*Terraces along Tres Pinos Creek*

The beds in the rock-covered hills are Meganos in age and Meganos also outcrops along the canyon in the center of the picture. The hills in the background are made up of Chico and Meganos strata. The valley between is filled with Pleistocene and the terraces are capped with Quaternary gravels.

Cretaceous thrust over Eocene.—Figure 6 represents a structural section across the strike of the strata in this area. The section runs along a line practically parallel to the small wooded canyon in the center of the photograph, figure 7. The main features brought out are a denuded anticline containing Cretaceous and Eocene rocks and a thrust of Cretaceous over Eocene on one limb of the anticline. The exposures are excellent, and fossils were collected in the Eocene on both sids of the anticline. Cretaceous fossils were also found in the beds north of the fault. The thrust-plane in this case is one of the old faults of the San Benito region, the movement probably occurring before the deposition of the Pleistocene.

Post-Pleistocene floodplain.—This same locality, shown in figure 7, also has well defined terraces with projecting hog-backs. These terraces

do not resemble the faulted river terraces along the San Benito River in the vicinity of Bird Creek, but are normal terraces formed during the uplift of the Santa Clara Valley and represent the old shoreline of the embayment that once occupied the Santa Clara Valley. The gravels which underlie the terraces are partly outwash from the near-by hills, since in places the old stream channels may be traced back to the oldland. The old surface truncates strata ranging from Pleistocene to Franciscan in age, inclusive, without any topographic break. It seems clear that the upper terrace surface and the surface of the mature hills in the background of the photograph (figure 7) were formed in post-Pleistocene time.

MAIN PLEISTOCENE AREA

General statement.—One of the unique features of this region is the thrust-faulting in soft Quaternary rocks. South of the denuded anticline

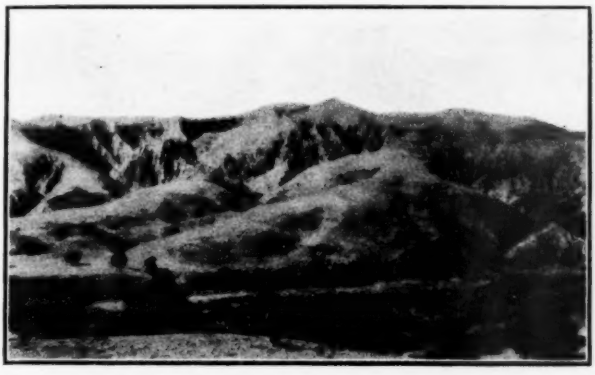


FIGURE 8.—*Exposures of Pleistocene Beds along Los Muertos Creek* Showing typical Pleistocene cliffs.

just discussed is an area of Pleistocene rocks in which one may observe post-Pleistocene thrust-faults along which evidence of recent movement is found.

Faults in Pleistocene exposing Franciscan.—The section bounded on the west by Tres Pinos Creek (see figure 3) contains Pleistocene which lies unconformably both upon Cretaceous and Franciscan. The Pleistocene strata are cut in places, however, in such a way as to produce striking cliffs and show remarkable sections. These cliffs extend to the crests of the hills, rising from 500 to 1,500 feet above the surrounding valley floor. The Franciscan is exposed in a number of places at the bases of

the cliffs and on the opposite gentle slopes, showing that the cliff has been formed by erosion of the upper strata which must have been lifted by movements in the underlying hard rock. The cliffs are in many cases markers of thrust-faults and may in fact be considered as weathered thrust-scarps. Faults produced by this uplift can be traced structurally; in fact, it is possible to find places where Franciscan rocks have been thrust over the Cretaceous.

Topographic features of active thrust-faults.—The Pleistocene gravels northwest of Los Muertos Creek have a dip that is for the most part about parallel to the slope of the hill. In a few places the beds have been slightly tilted and broken, forming steep cliffs that border sharp,

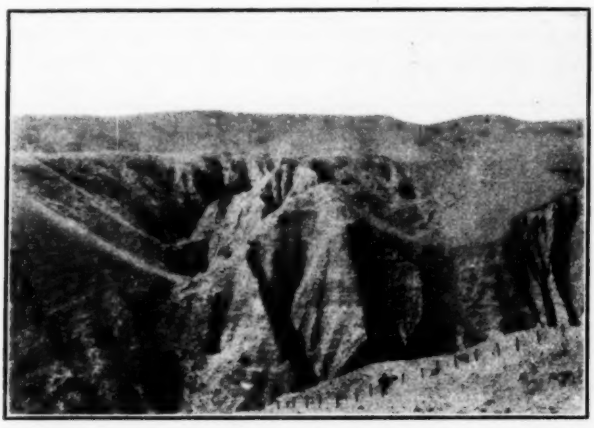


FIGURE 9.—*Caves produced by slumping in the soft Pleistocene Beds*
This is due to movement in the underlying formations.

rugged canyons. The weathering of these cliffs is illustrated in figure 8, while the type of canyon bottom formed appears in figure 9.

The mechanics of the formation of the type of canyon illustrated in figure 9 are interesting. The Pleistocene beds rest unconformably upon Cretaceous sandstones and shales that show high angle dips (for the most part 80 to 90 degrees) where exposed around the edges of the Pleistocene. These Cretaceous beds have been closely folded and in some cases faulted. Furthermore, where this movement is still going on and taking place beneath the Pleistocene the overlying gravel beds are being broken and the processes of erosion materially hastened. The undercutting and caving of cliffs then occurs, and even the smooth slopes are soon broken and cut

gullies with stream channels that work their way gradually either to the grade[20] of the main drainage or to the top of the harder Cretaceous beds. This, it must be understood, takes place in a locality having a rather small rainfall. If the precipitation were heavy, the entire region would probably have long since been leveled by erosion.

The most evident area of thrusting in the Pleistocene is illustrated diagrammatically in figure 10. The ridge shown in the sketch contains a very shallow syncline with northwesterly dips of not over five degrees on the limb toward the San Andreas Fault and equally small dips on the Tres Pinos side. The syncline is cut, however, by minor uplifts across the axis. These uplifts expose cliffs of Pleistocene strata having beds tilted to an angle of 17 or 18 degrees and occasionally even 20 degrees. The tilted strata pitch at a slight angle to the synclinal axis; thus the syncline is broken at the cliffs. Each cliff facing the direction just described marks the

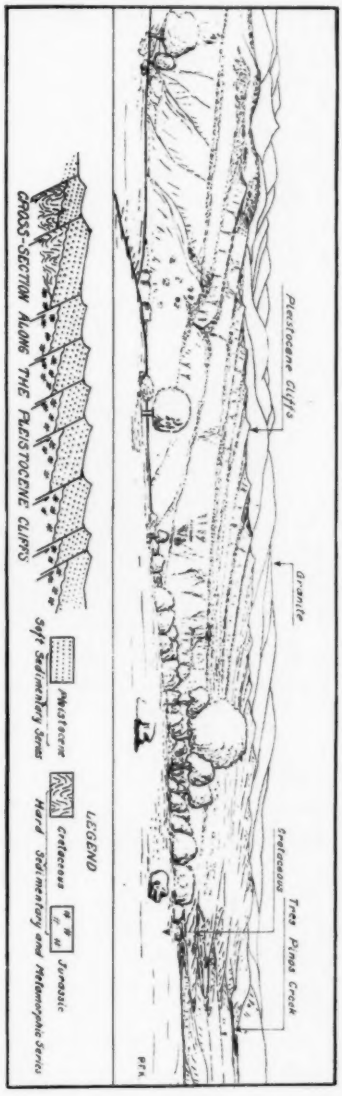


FIGURE 10.—*Diagram illustrating Thrust-faults*

These thrust-faults are indicated by a series of cliffs in the Pleistocene east of the San Andreas fault and west of Tres Pinos Creek. This is part of the main Pleistocene area.

[20] A stream that has attained the minimum slope under the existing conditions is said to have reached *grade*. This need not be *baselevel*, which is an imaginary extension of sealevel under the land.

edge of a block that has been thrust upward, the direction of release of pressure being uniformly toward the southeast. The main effect, however, is due to movement in the underlying rock, which, from the character of occasional outcrops on the western side of the ridge, is judged to be mainly Franciscan, but probably also partly Knoxville. Franciscan schist, quartzite, and serpentine outcrop along the ridge just mentioned, and in addition are outcrops of sandstones carrying Knoxville fossils. Franciscan is in turn thrust over Pliocene sandstone (as will be shown in a later section). The directions of thrusting often agree, thus indicating that the movement which is taking place beneath the Pleistocene is possibly a continuation of the same deformation responsible for the thrust of Franciscan over Pliocene.

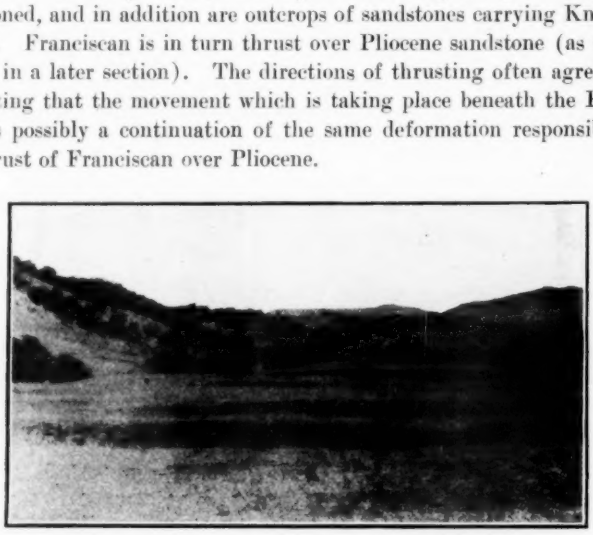


FIGURE 11.—*Rift Zone due to recent Fault Movements in the Pleistocene*

The rift in the immediate foreground is about 8 feet high. Comparison of objects with the herd of cattle on extreme right will give some idea of dimensions.

The traces of the fault-lines on the surface are, in general, U-shaped, but with certain irregularities. On the west they join with a few main faults that in turn run out to the San Andreas Fault. On the east they seem to end before they reach Tres Pinos Creek. No evidence of faulting along this creek could be observed, since strata may be traced across the creek without interruption in a number of places. The only exception was noted at the junction of the latter creek with Los Muertos Creek, where a minor fault crosses Tres Pinos Creek and runs for a short distance southeast of Los Muertos Creek.

Rifts and slumping.—The age of the faulting discussed in the preceding paragraph is post-Pleistocene and the movement is continuing at the present time. Actual rifts are exposed on the ridge above Sulphur Creek

(figure 3, southeastern edge) and furnish the best evidence of recent movement. These rifts appear on an even slope at the base of a cliff and cover about thirty acres. They cut the field into numerous parallel scarps averaging from 6 to 10 feet in height. (A photograph of the feature is shown in figure 11.) The young faults here are in Pleistocene rocks which have been broken, due to movement in the underlying formations. Doubtless hard strata would be folded under similar pressure, but the soft Pleistocene is broken.

Another example of slumping is on the east of the San Andreas Fault, in the vicinity of the junction of Willow Creek with the San Benito River (see figure 12). This region resembles a huge landslide with a very low angle slope, as one looks at it from a distance. However, the word "landslide" does not seem exactly explanatory of the phenomena observed. Some sliding has beyond doubt occurred, but the major breaking of the slope, which has produced an irregular surface, is due to faulting consequent on the uplift of the hill shown in the background. The maximum slope is not over 15 degrees, and in other places material

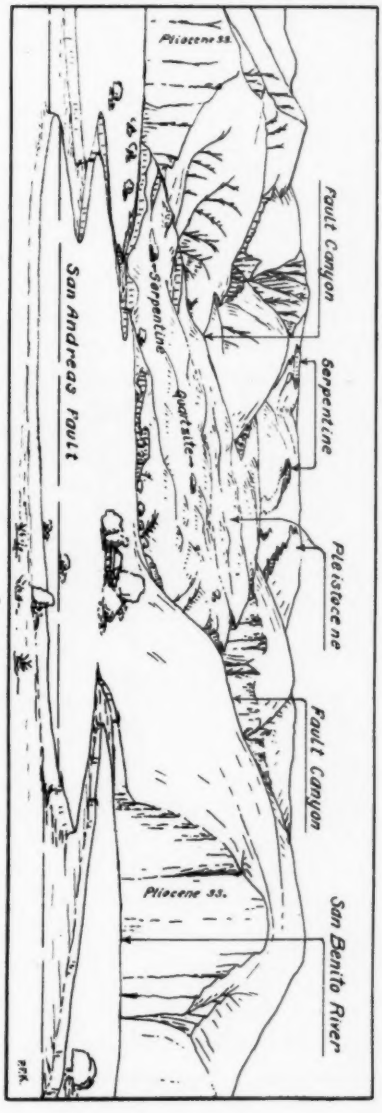


FIGURE 12.—*Slumping and Erosion of soft Pleistocene and Pliocene Sedimentaries*
These sedimentaries overlie fault lines in hard Franciscan metamorphic rocks.

of the same nature shows the ability under prevalent climatic conditions to retain vertical cliffs 500 feet in height. Faults bound the broken area on three sides; the one on the lower side is the San Andreas Fault. The other two may be accurately located—one by offsets in Pliocene strata and the other by the thrust of Franciscan over Pliocene. It is probable that small faults in some places run into the broken area. These faults are in part responsible for the slumping. Similar rift features may be observed in other parts of the area along the San Andreas Fault where the angle of repose is so low that there is no reason to expect a landslide. Exposures of closely folded Franciscan chert occur in the broken area in contact with Pliocene sandstone and Pleistocene gravel. In nearby hills the Pliocene strata have sufficient strength to stand in cliffs several hundred feet in height. If the slumping under discussion were entirely a landslide feature, one would expect to see slides developing on the steep cliff where the angle of slope is considerably greater than in the zone of slumping. Such landslides, moreover, do not appear where faulting is not in evidence; at least, it is reason-

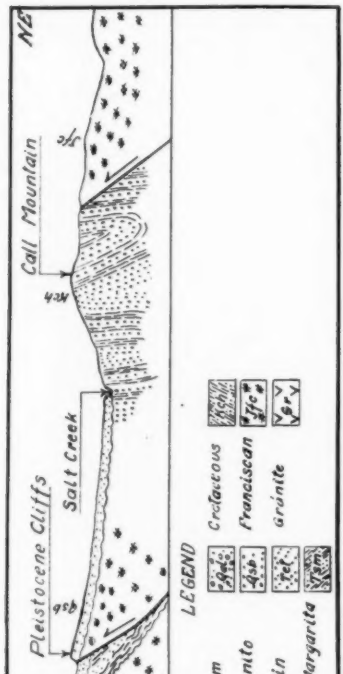


FIGURE 13.—*Generalized Section East of the Great Faults*

This section is across Call Mountain and the Pleistocene cliffs, bearing about north 25 degrees east and 9 miles in length in the extreme southeast of the area studied.

able to consider areas such as this as zones of slumping accompanying fault movements, and probably this feature represents the apearance of the front of a thrust in the process of forming.

POST-PLIOCENE MOVEMENT

A final instance of thrusting is that which occurs in the marine Pliocene (Etchegoin) in the southern part of the area (figure 3). Movement following the Pliocene and preceding the Pleistocene took place in this district. A generalized section showing the character of this movement is shown in figure 13. The section runs from the vicinity of Salt Creek to the San Andreas Fault (figure 3) and includes the Franciscan, Cretaceous, Miocene (Santa Margarita), Pliocene (Etchegoin), and Pleistocene formations. The outstanding features are the thrusting of the Franciscan over the Cretaceous, the tilting of the Pleistocene by movements in the underlying Franciscan and Cretaceous, and the thrust of Franciscan over Pliocene. The folding of the Pliocene and thrusting of the Franciscan against it shows movement of post-Pliocene age. Deposition of comparatively horizontal Pleistocene strata indicates a period of sedimentation following the Pliocene uplift, while a still later uplift and faulting dates from the close of Pleistocene deposition to the present. It is probable that in many places the later movements have continued along the older fault-lines. The outstanding example of this is, of course, the San Andreas Fault, which has been a zone of weakness throughout a long stretch of time—at least from Mesozoic to the present.

CONCLUSION

The stratigraphic portion of this paper discusses formations ranging from pre-Cretaceous time to Recent. Knoxville and Chico Cretaceous are established on fossil evidence, Meganos Eocene is identified for the first time in this vicinity; Oligocene is first definitely recorded in the vicinity of San Juan Bautista; the Pliocene is divided with certainty into marine and continental; and the first recognition is made of a large area of Pleistocene sediments along the course of Tres Pinos Creek.

The structural portion of the paper deals chiefly with thrust-faulting in Tertiary and Quaternary strata. Since the beginning of the Tertiary, there have been two periods of movement of known age in the San Benito Region: first, extensive folding and faulting, followed the period of Pliocene deposition; and, second, at the close of the period of Pleistocene sedimentation there began a period of uplift accompanied by faulting which is continuing at the present time. These movements are in addi-

tion to those which took place in the late Jurassic or in the Cretaceous, which were too complex in nature to be interpreted with the information at hand.

The type of movement on the fault-lines is usually one of thrusting. Along the recent faults there are several directions of pressure which produce a system of thrust-blocks. The period of thrusting has had a duration involving several geologic epochs. In addition to the faults just mentioned is the San Andreas Fault, which has been a major line of movement since the Cretaceous.

The topographic expression of the faults is striking. In the vicinity of San Juan Bautista, west of the San Andreas Fault, a system of blocks is produced with sharp declivities facing northward and even gentle slopes toward the south. This system extends from Pajaro Canyon south into the Gabilan Range. East of the San Andreas Fault another system of blocks, reversed in direction (with gentle, smooth slopes toward the north), extends from the Santa Clara Valley south to Sulphur Creek. The boundaries of these blocks are faults which have been established on geologic evidence.

The smooth slopes of several blocks east of the main fault are parts of a post-Pleistocene erosion surface which suffered faulted uplift. Remarkable cliff sections in soft Pleistocene gravels are due to movement in the underlying hard strata. Extensive slumps occur which are usually at least a partial result of fault movement.

The study as a whole has shown that the general direction of the release of pressure west of the San Andreas Fault is toward the northwest; the direction of the release of pressure east of the fault is toward the southeast; and the great fault is the line of weakness between.

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EROSIONAL CYCLES IN THE FRONT RANGE OF COLORADO AND THEIR CORRELATION[1]

BY HOMER P. LITTLE

(Presented in abstract before the Society December 29, 1924)

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INTRODUCTION

This paper is the result of work done during July and early August in the summer of 1924. The work was financed by Clark University and received the cordial cooperation of the United States Geological Survey. Particular thanks are due to W. C. Mendenhall, of the Washington office, and C. W. Henderson, of the Denver office. The writer was assisted in the field during the season by Rollin Atwood and in the last few days had the benefit of the field advice of Wallace W. Atwood and Kirtley Mather.

The objective of the work was the study of the peneplains of the Front Range with a view to applying the facts brought out by Lee's work in Rocky Mountain National Park to other parts of the range and adding such new facts to its erosional history as could be discovered. It was especially desired to establish more definitely than previously the age of

[1] Manuscript received by the Secretary of the Society April 13, 1925.

FIGURE 1.—*Index Map*

the major peneplains, and to establish a correlation with those of other portions of the Rocky Mountains. In this work most of the mountain roads between Colorado Springs and Estes Park were penetrated, as well as much of the adjoining region; a rapid survey was then made of the territory from Estes Park northward to Tie Siding, in southern Wyoming, where Blackwelder described the Sherman peneplain, and thence to Glendevey and Green Ridge, a splendid remnant, for knowledge of whose existence the writer is indebted to Dean Worcester, of the University of Colorado (figure 1). South from Colorado Springs the area of the Royal Gorge was penetrated, and for the sake of comparison the writer undertook a three weeks' trip to the San Juan Mountains with Wallace W. Atwood to examine the peneplains described by him there.

New evidence of the age of the peneplains from observation within the range itself was not obtained, but Mather, from observations to the northeast of Fort Collins, secured very definite evidence, and it seems safe to correlate most of his stages with those of the Front Range.

Many published articles were of assistance in the work, especially those of Ball, Davis, Blackwelder, and Lee. These and other articles consulted are listed at the end of the paper, but do not comprise a complete bibliography of the subject.

Peneplains of the Front Range

General statement

For practical purposes, though not with absolute accuracy, the peneplains of the Front Range may be considered as cut wholly across pre-Cambrian granites, gneisses, and schists, with the former especially abundant. Except on the steepest slopes, the region traversed by roads is covered with the coarse sand characteristic of disintegrated but undecomposed granite. Soils are occasionally evident, as in road cuts just south of Bergen Park. These, however, are in the majority of cases the products of weathering of the less resistant schistose rocks.

The erosional history of the Front Range will be described under the headings Flattop Peneplain, Rocky Mountain Peneplain, Park Cycle, Fountain Creek Cycle, and Canyon-cutting Cycle. Of these terms, the third and fourth are here used for the first time.

Discussion of these surfaces groups around four areas where remnants are particularly conspicuous, namely, the Pikes Peak region, the Bergen Park-Evergreen region, the Rollinsville-Nederland-Ward region, and the Estes Park and Vicinity region.

THE FLATTOP PENEPLAIN

The Flattop peneplain was so named by Lee in 1917 because of the wide extent of its development on Flattop Mountain, in Rocky Mountain National Park. Here it occurs at an elevation of 12,300 feet. He correlated it with the surface described by Ball in the Georgetown Quadrangle, and the latter's description will serve for the region as a whole:

> "The mountainous upland was an ancient land surface with about the same relief as the present surface. Dome-shaped mountains and broad, smoothly contoured ridges, however, stood where sharp peaks and rugged ridges now are. . . . The drainage was dendritic and mature. . . . The remnants of this old topographic surface are covered by rock residuals and in many places by deep soil."

The surface of Flattop Mountain is, as said above, the type area (figure 2). The shoulders of Hagues Peak, when seen from any point in Estes Park, show the old surface almost as well (figure 3), and considerable areas may be seen along Trail Ridge, which is easily accessible from Fall River Pass. Twenty-five miles to the south, along the Continental Divide, are the peneplain remnants at Corona described by Davis, also at an elevation of about 12,000 feet. A few more miles to the southward, and visible from Corona, is the extensive remnant from the western edge of which James Peak rises as a prominent monadnock to a height of over 13,000 feet. A large remnant previously undescribed occurs near the point where the Continental Divide makes its turn to the west, about 10 miles southwest of James Peake. This remnant, which is one of the largest and most level areas in the entire region (figure 4), is easily visible northwest of Berthoud Pass. Its position may be determined from the road by the flat crest line of the large cirque which is cut into its surface. Although this remnant is off the topographic map, its elevation relative to Berthoud Pass shows that it must be at least 11,500 feet in altitude.

Another ten miles to the south is the Georgetown area described by Ball. This rather inaccessible area was not studied in detail. However, the proposed road to Mount Evans, which now extends to within three miles in an air line from the mountain, was traversed to its end. From this the mature topography of the upland country is strikingly evident. The suggestion is made that the somewhat even-crested ridge extending for three miles west of Chief Mountain at an elevation of 11,000 feet may represent the Flattop surface, and the great mature areas[2] south and west

[2] This area and much of that to the east and south may be best studied from the Denver Mountain Parks sheet, advance copies of which were available for use in the field through the courtesy of the Denver office of the U. S. Geological Survey.

FIGURE 2.—*Surface of Flattop Peneplain*

Flattop Mountain in the foreground. Altitude, 12,300 feet. The monadnock of Hallett Peak is at the left and Longs Peak in the distance.

FIGURE 3.—*Hagues Peak from Prospect Mountain, Estes Park*

The flat shoulders of Hagues Peak represent the Flattop peneplain. The ridge in the middle ground—elevation, 10,000 feet—represents the Rocky Mountain peneplain, and the low area in the foreground the Park stage.

of Mount Evans, although not visited, may be conjectured from the map to represent other remnants. The flat summit of Meridian Hill, eight miles east of Mount Evans, with an elevation of 11,400 feet, may also be an isolated remnant.

To the southward no other remnants of the old plain were definitely recognized. The wide extent of the Rocky Mountain surface in this region, however, readily explains their absence. It is probable that the great spurs extending out from Pikes Peak at an altitude of about 12,000 feet are remnants of the Flattop plain rather than upfaulted parts of the Rocky Mountain surface, as Finlay supposes. The crest line of the Tarryall Mountains, six miles long, with fourteen distinct knobs, all of which reach elevations between 11,700 and 12,400 feet, is also suggestive. This range lies midway between Pikes Peak and Mount Evans, though not in a direct line. The region west of the Tarryalls is not yet mapped. In this connection credit should be given Richardson for his earlier observation that Devils Head (9,318 feet) and other isolated peaks west of the area of the Castle Rock Folio may be remnants of an older surface that withstood the general denudation of the Rocky Mountain cycle.

It is clear from the above that from the northern boundary of Rocky Mountain National Park to a point south of Mount Evans remnants of a mature topography at an elevation of about 12,000 feet are so numerous as to indicate the former presence of a continuous surface. Although south of this area remnants are not so common, its presence as far south as Pikes Peak may probably be assumed.

Lee has hazarded the suggestion that a peneplain still older than the Flattop surface may be represented by the summit of Longs Peak (figure 2) and other of the higher mountains in Colorado. Davis has pointed out that there are forty-two summits in Colorado between 13,500 and 14,000 feet, thirty-nine between 14,000 and 14,500 feet, and none higher than 14,500 feet. These facts are suggestive, although the remnants seem too few and the summit areas too small to permit of a definite hypothesis.

THE ROCKY MOUNTAIN PENEPLAIN

The writer has not been able to discover the first use of the term Rocky Mountain peneplain, but Lee refers to it in 1917 as a term commonly in use. In contrast to the Flattop peneplain, it finds its best development in the southern part of the area studied—the Pikes Peak region. Near the abandoned mining town of Gillett, four miles northeast of Cripple Creek, it stretches two miles north and south over the old granite surface

FIGURE 4.—*Large remnant of Flattop Peneplain, west of Berthoud Pass*
Elevation, about 11,500 feet.

FIGURE 5.—*Rocky Mountain Peneplain Surface*
On this surface lies the town of Gillett, near the southwest base of Pikes Peak. Elevation, 10,000 feet.

with an almost tablelike flatness (figure 5). Here its altitude is 10,000 feet. Farther north, opposite Palmer Lake, it is about 9,200 feet in altitude. Instead of being continuous here, it has been dissected by a dendritic drainage into a maze of promontories rising sharply above the recent valleys (figure 6). Viewed from a distance, these promontories merge to give the effect of a continuous surface. North and west of here, toward the South Platte River, the surface of the plateau drops to an altitude of 7,400 to 8,000 feet. This sag in the surface can be clearly seen from various points; it was observed especially clearly from the knoll where the road bends toward Palmer Lake, as shown at the eastern edge of the Platte Canyon sheet ten miles south of Stone Canyon. Farther north, in the Bergen Park area, the peneplain surface is far less well preserved. For the purpose of classifying the region physiographically, the general view from Genesee Mountain, five miles southwest of Golden, is most satisfactory. From here it is evident that the peneplain is represented only by most discontinuous fragments, which rise abruptly from a younger late mature erosion surface. The eastern and western spurs of Genesee Mountain and the summit areas of Lookout Mountain, Bear Mountain, and Doublehead Mountain, as well as other unnamed summits, are probable remnants; also other areas to the south, which occur at altitudes of from 7,600 feet to 9,000 feet. If these areas are correctly identified, the surface of the peneplain has been considerably warped or faulted in this area. Farther west, toward the crest of the range, are flattish remnants which may represent its inner margin. The chief area which may be so interpreted is the large flat surface immediately southwest of Meridian Peak, at an altitude of about 10,800 feet. Accepting this as a remnant, the plain in this region has a slope of 175 feet per mile eastward.

The area between Idaho Springs and Central City and westward toward the crest of the range is so dissected that little of it can with any definiteness be considered to represent a previous erosion cycle. To the northeast of Central City, however, along the westward margin of the Black Hawk sheet and extending for a number of miles toward Rollinsville, the late mature topography is clearly evident at an altitude of 9,000 to 9,200 feet. Thorodin and Tremont mountains rise from this surface as unusually jagged monadnocks. To the north the elevation declines to about 8,500 feet. The region is quite thoroughly dissected by canyons and short steep gulches, but when viewed from a vantage point, as near the town of Ward, the canyons and gulches take on less prominence and the plateau remnants far more, furnishing one of the finest views of a dis-

FIGURE 6.—*Surface of Rocky Mountain Peneplain west of Palmer Lake*
Elevation, 9,200 feet. The valleys do not belong to the present cycle, but were probably eroded in the Park Stage.

FIGURE 7.—*Dissected Rocky Mountain Peneplain Surface overlooking Ward*
Elevation, 8,500 feet

sected peneplain to be seen anywhere (figure 7). As Ward is approached, the elevation increases to upward of 9,300 feet or perhaps more. About one mile to the northeast the highway runs for a mile over a wholly undissected remnant of the plateau (figure 8). From Ward northward for twelve miles toward Allens Park the remnants become increasingly small, until they completely disappear in the modern mature topography. The area to the east is unmapped. No further remnants to the northward are identified with certainty until the Rocky Mountain National Park is entered.

Immediately west of the Rollinsville-Ward area just described are three striking remnants of the Rocky Mountain peneplain, known as Caribou Flat, Chittenden Mountain, and Guinn Mountain—Bryan Mountain (figure 9). Because of increased elevation of the peneplain surface toward the Continental Divide, these remnants are much higher than those found farther east—10,250 feet for much of Caribou Flat and 11,000 feet for much of Chittenden and Guinn Mountains. The sharp break between these high level remnants of the Rocky Mountain surface and the Flattop surface at Corona near by furnishes one of the chief arguments in favor of the existence of two separate peneplains (figure 10).

The Rocky Mountain peneplain is represented by no continuous surfaces north of Allens Park, at least in none of the area yet mapped. In Estes Park, however, as Lee has pointed out, numerous peaks reach altitudes corresponding to those of areas farther south. This includes Giantrack Mountain, Deer Mountain, the ridge of which The Needles is the culminating point, and Prospect Mountain. These range in elevation from 8,800 to 10,000 feet. There is a small, strikingly flat area at the very head of Tahosa Valley, midway between Allens Park and Estes Park, which the writer is inclined to regard as a remnant, adding one more link to the chain which connects the various areas and shows them to be remnants of a common surface.

THE PARK STAGE

The name Park Stage is proposed for a mature to late mature topography which has been eroded below the Rocky Mountain surface at various localities (figure 6). Its presence seems to have escaped the notice of previous workers, although in several instances it is a most striking feature and contrasts strongly with the canyons downstream and the isolated remnants of the Rocky Mountain peneplain which rise above. There are three regions in which it is best developed: the Woodland Park-Divide area north of Pikes Peak, the Evergreen-Bergen Park

FIGURE 8.—*Undissected Rocky Mountian Peneplain Surface three Miles North of Ward*

FIGURE 9.—*Looking Southwest over Caribou Flat toward Corona*
Showing inner edge of Rocky Mountain peneplain.

area, about eight miles southwest of Golden, and the Estes Park area. In the first two regions especially it is of considerable extent and is the most evident of all the surfaces. In contrast to the older surfaces these remnants can not, because of their less complete development, be traced from basin to basin. Their slope is in all cases toward existing valleys.

In the vicinity of Woodland Park and Divide is clear evidence that this stage was interrupted by a glacial episode. On the retreat of the ice, erosion began again and has dissected the glacial deposits into a stream-cut topography of dendritic type. All trace of glacial action has been

FIGURE 10.—*Looking Northwest from Flattop Peneplain at Corona, over the inner Edge of the Rocky Mountain Peneplain*

Elevation of inner edge, 11,000 feet. Difference in elevation of the two surfaces, about 1,000 feet.

removed save a few erratics, but from numerous road cuts striated cobbles have been collected, leaving no question as to the origin of the materials. The elevation of this surface varies approximately from 8,300 to 9,300 feet. The transition from the Park Stage surface to the Rocky Mountain peneplain is in some places almost imperceptible; at other localities, where distinct monadnocks occur, it is abrupt.

In the Bergen Park-Evergreen area the surface occurs at elevations varying by gentle slopes from 7,000 to 8,000 feet. The canyons occupying the lower ends of the valleys flow in meandering courses probably

inherited from this stage. Wide terraces in the rock high above the present stream but below the Rocky Mountain surface are visible in the canyons, as in the canyon of Bear Creek below Evergreen. These are best seen, however, in the Estes Park region.

In Estes Park the areas representing this episode lie 1,000 feet or more below the Rocky Mountain peneplain, in a series of late mature valleys (figure 3). The road south from Estes Park traverses one of these valleys, and the valley of Fish Creek southeast of Prospect Mountain is of a similar nature. On leaving Estes Park by Big Thompson Canyon the pronounced meandering nature of this stream is evident, some of the incised meanders being of striking perfection. Wide benches appear above the stream—sometimes on one side, sometimes on the other, sometimes on both. These benches are higher above the present stream the farther downstream one progresses. The meandering course is evidently inherited from a time when the upper mature valleys of Big Thompson River had its outlet at the level of this bench, and the present intrenched meanders may be inherited from that stage, due to recent uplift. The absence of a topographic map of the canyon to the east, however, makes it impossible to say how the level of the bench compares with the level of the wide valley of Estes Park, and it may represent the equivalent of the Fountain Creek (which see) rather than the Park stage.

A hurried trip to the north showed the presence of a similar cycle just to the west of Livermore. This area is described in detail by Mather in a paper abstracted in the current volume of this Bulletin. In it he recognizes an upper bench within the canyons, which he makes part of the canyon cycle rather than correlating it with the Alford stage, which corresponds to the Park stage.

THE FOUNTAIN CREEK STAGE

Here and there evidences of an additional minor stage are found intermediate between the Park stage and the present Canyon-cutting stage. At only one place was the presence of such a stage clearly shown, namely, in Fountain Creek, which runs from Woodland Park through Manitou to Colorado Springs and beyond. Because of this fact, the name Fountain Creek stage is suggested. It is represented by the flat inner valley of this creek, which persists for several miles upstream from a point a mile above Green Mountain Falls (Pikes Peak sheet). It merges upstream with the Park stage, while downstream the canyon has destroyed all traces of its presence.

This stage is, as said, of minor importance, but is interesting as occupy-

	WESTERN WYOMING		SOUTHEAST WYOMING		FRONT RANGE → COLORADO ← SAN JUAN MOUNTAINS				SOUTHEAST → IDAHO ← CENTRAL			BUTTE → MONT. ← BEARTOOTH MTS	
EPOCH	WEGTOATE BRANDON	BLACKWELDER	BLACKWELDER	MATHER	FINLAY RICHARDSON	LEE	LITTLE AND ATWOOD	ATWOOD AND MATHER	MANSFIELD	UMPLEBY	BUWALDA	ATWOOD	BEVAN
RECENT				BELLVUE CYCLE			CANYON CUTTING CYCLE	CANYON CUTTING CYCLE	SPRING CREEK GIBSON			FOURTH CYCLE OF EROSION	
PLEISTOCENE	PLAIN #1 / PLAIN #2 / PLAINS 3-4		HECLA CANYONS / LESLIE VALLEYS (NEITHER OF ABOVE OLDER THAN PLIOCENE)	LIVERMORE CYCLE / ALFORD CYCLE			FOUNTAIN CREEK CYCLE / PARKS STAGE	OXFORD VALLEYS / BOULDER-MESA EROSION SURFACE	LATE GLACIAL / PUTNAM GANNETT				SUBSUMMIT PENEPLAIN PERHAPS COMPLETED DURING PLIOCENE
PLIOCENE		WIND RIVER SUMMIT PENEPLAIN	SHERMAN PENEPLAIN (AT LEAST POST MID-TERTIARY)	ROCKY MTN PENEPLAIN		ROCKY MTN PENEPLAIN TERMINATED AT CLOSE OF TERTIARY	ROCKY MTN. PENEPLAIN	SUMMIT PENEPLAIN					
MIOCENE									TYGEE CYCLE (PERHAPS IN PART EARLY PLIOCENE)			THIRD CYCLE OF EROSION	SUMMIT-PENEPLAIN (NOT OLDER THAN MIOCENE)
OLIGOCENE	SUMMIT-PENE-PLAIN COMPLETED BY MID TERTIARY				PENEPLAIN BY CLOSE OF OLIGOCENE	FLAT TOP PENEPLAIN (COMPLETED SOME WHERE NEAR MIDTERTIARY)			SNOWDRIFT PENEPLAIN (PRE MIDDLE MIOCENE)		PENEPLAIN BASED ON NEW AGE DETERMINATION OF PAYETTE FORMATION	SECOND CYCLE OF EROSION	
EOCENE			MEDICINE BOW PENEPLAIN	FLAT TOP PENEPLAIN			FLAT TOP PENEPLAIN	EOCENE PENEPLAIN		EOCENE PENEPLAIN		EOCENE PENEPLAIN	

FIGURE 11.—*Table showing Erosion Cycles of Front Range and adjacent Areas as recognized by various Writers*

Each cycle terminates at approximately the position of the solid lines.

ing approximately the position that has been assigned to minor stages in other areas.

THE CANYON-CUTTING STAGE

As is well known, the streams of the Front Range leave the mountains by canyons due to recent uplift. The writer has nothing new to offer in this connection.

Age and Correlation of Erosion Cycles

The age of the Flattop and Rocky Mountain peneplains was not fixed by the writer's studies any more definitely than previously indicated by Lee. Mather, however, who was in touch with the party in Estes Park, has correlated the peneplains previously described by Blackwelder in southeast Wyoming with sedimentary deposits on the plains, and will publish their ages as Eocene and Pliocene or earliest Pleistocene respectively. He recognizes, however, that the Flattop cycle may have persisted into early Oligocene. These peneplains are considered by Mather, as well as all who have been in the field with the writer, as undoubted equivalents of Flattop and Rocky Mountain peneplains. Dean Worcester, who has been giving detailed study to the problem, has also expressed orally his view that the Sherman peneplain can be traced directly into the Rocky Mountain peneplain.

The writer had hoped to get some clue to the age of the lower peneplain by its relations to the Florissant basin, but nothing definite was established. The Rocky Mountain peneplain comes up sharply to the border of the basin, which contains undoubted Oligocene deposits. If these deposits occur in a basin formed by erosion or down-warping or faulting in the Rocky Mountain surface, that surface is, of course, older than Oligocene. Such an age is entirely out of harmony with that determined for what is considered the northern extension of the same surface. Another possibility is to consider that the Florissant was deposited in a basin formed by warping in the Flattop surface, and that later the Rocky Mountain peneplain was developed by erosion across granite and lake bed surfaces alike. Differential erosion then produced the present topography. If it were not for the clear development of two distinct surfaces to the north, the relations at Florissant might lead one to adopt Finlay's view, that what is now distinguished as Flattop and Rocky Mountain peneplains are simply segments of the same surface displaced by faulting.

The Park stage occupies about the position of the Leslie valleys recognized by Blackwelder and the Boulder Mesa recognized by Atwood and Mather in the San Juan Mountains, and probably all were formed at

Each cycle terminates at approximately the position of the solid lines.

about the same time. The Fountain Creek stage is too local to attempt any definite correlations, but it is interesting to note that a similar short stage occurred toward the close of the Pleistocene in several separated regions. The Canyon cycle has long been recognized as representing the last great uplift. These relations are brought out more completely on the accompanying table (figure 11).

It should be recognized that correlations of these cycles does not involve the belief that the corresponding present surfaces are of the same age. A great erosion cycle may, for instance, have been brought to a close with the Eocene in one section of the mountains and have persisted into early or even late Oligocene in another. In such a case there may be a rough correlation of the cycles, though not of the surfaces. Viewed thus, it seems safe to recognize three great periods of post-Cretaceous erosion, one cycle persisting through the Eocene over wide areas and brought to a close during the Oligocene, in most cases in early Oligocene; another cycle, widespread but probably less exactly contemporaneous, occurring in middle to late Tertiary time; and a third cycle, widespread but shorter-lived, occurring in several areas in late Pliocene to early Pleistocene time.

Discussion

Prof. Francis P. Shepard: The correlation of peneplains depends on the assumption that they are contemporaneous. If we *assume* they are not contemporaneous, it is equally easy to *show* that they are not contemporaneous.

Prof. Eliot Blackwelder: Since reference has been made to my paper on the Laramie District (1908), I feel obliged to say that I no longer subscribe to some of the views on physiographic history expressed therein. I am particularly doubtful about the ages of the earlier stages.

Mr. Frederick K. Morris: In one of the illustrations Professor Little showed the Flattop peneplain as a shoulder or bench from which a monadnock rises, apparently with tower-like abruptness. It looked in the picture like the "inselberg" of Passarge or the "girdled mountain" of Keyes. Could such monadnocks point toward an arid climate in the closing stages of the Flattop peneplanation?

To Professor Shepard: Professor Shepard's position would be well taken if we were trying to show that these peneplains *ended* contemporaneously. However, we are speaking of the general contemporaneity of the *cycle* and not the precise *end* of the cycle. From this point of view it seems to me that they are in a very real way largely contempo-

raneous. The period during which each cycle of erosion occurred has been determined by geologic field methods.

To Professor BLACKWELDER: I have merely attempted to show in outline form Professor Blackwelder's published statements. It is interesting to note that Professor Mather, after working on the plains near this region during the summer of 1924, has reached conclusions as to the age of the peneplains quite similar to those expressed by Professor Blackwelder in the paper referred to.

To Mr. MORRIS: I presume that the illustration to which Mr. Morris refers is the one that shows Hallett Peak rising abruptly above the Flattop peneplain of Flattop Mountain. I think that this abruptness is due to mechanical weathering at high altitudes, in addition to the fact that a large cirque cuts into the peneplain almost immediately at the edge of Hallett Peak. Near-by extensive areas of the Flattop peneplain, as at Trail Ridge and the vicinity of Mount Evans, show none of this abruptness, but rather well-rounded, dome-shaped hills. I would not regard the monadnock referred to as justifying any conclusions as to the climate in the closing stage of Flattop peneplanation.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 36, PP. 513-520 SEPTEMBER 30, 1925

REMARKABLE ADIRONDACK GLACIAL LAKE*

BY WILLIAM J. MILLER

(*Presented before the Society December 30, 1924*)

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INTRODUCTION

A recent examination of the Hudson-Schroon valleys of the southeastern Adirondack region has furnished evidence that a remarkable, long, narrow glacial lake, with branching arms, lay in those valleys during the waning of the last great ice-sheet in northern New York. Before the former existence of this extensive body of water was known, more or less evidence for the former existence of certain local portions of the lake was presented in a numbr of publications. Ogilvie in 1902[1] and again in 1905[2] and Kemp in 1910,[3] briefly referred to lake terraces in the valley of the Schroon River, in the Paradox Lake and Elizabethtown quadrangles respectively. Next was a brief description of Glacial Lake Warrensburg by the writer in 1911,[4] the lake phenomena being wonderfully exhibited in the vicinity of Warrensburg. In 1914[5] the writer again described this lake.

Another body of water, then thought to have been independent of and at a higher level than Lake Warrensburg, was described in 1914[5] as occur-

* Manuscript received by the Secretary of the Society March 30, 1925.
[1] References to list of publications at end of paper.

ring in the northern part of the Schroon Valley. This was called Glacial Lake Pottersville because of the fine display of the lake deposits in the vicinity of the village by that name. It was then suggested that the waters of this lake were ponded by a morainic dam across the Schroon Valley south of South Horicon. Lake Pottersville was again briefly described in 1916.[6] Stoller described his Lake Corinth in 1916[7] as a local body of water which occupied the general vicinity of the village of Corinth (Saratoga County), and he stated that "as the ice-sheet continued to withdraw to the north, a lake (Lake Corinth) developed, bounded by the belt of moraine on the south and having the ice-front as its northern margin."

Alling, in 1916,[8] suggested a correlation of the terraces previously described by Ogilvie and by Kemp in the upper Schroon Valley with those of Lake Pottersville. In 1923[9] the writer again described Lake Warrensburg with special reference to that portion which lay within the Luzerne Quadrangle. Still more recently an examination of the whole Hudson-Schroon Valley in the southeastern Adirondack region and a correlation of the lake deposits have led the writer to conclude that Lakes Warrensburg (including Lake Corinth on the south) and Pottersville were in reality but portions of a single, long, narrow, glacial lake which should be called Glacial Lake Warrensburg. No very detailed survey was made by the writer, but it is believed that the main facts are essentially as set forth in this paper.

Size, Shape, and Branches of the Lake

Lake Warrensburg lay in the Hudson-Schroon Valley, between South Corinth (Saratoga County) and Deadwater Pond (Essex County), a distance of nearly 70 miles. It was remarkably long and narrow, varying in width from less than one-fourth of a mile to about two miles, the average width having been not more than one mile (see accompanying map). It occupied a mountain valley whose steep sides nearly everywhere rose abruptly from the lake shores to heights varying from a few hundred to a thousand feet. The greatest depth of water in the lake is not known, but depths of 100 to 200 feet were very common.

Lake Warrensburg had many branching arms (see accompanying map), which caused it to have a dendritic shape. The principal body of water occupied the valley of the Hudson River to Warrensburg and thence northward the valley of the Schroon River. The main arms of the lake were as follows: 3 miles westward in the Sacandaga Valley; 3 miles northeastward in the Stewart Brook Valley; 13 miles north-northwest-

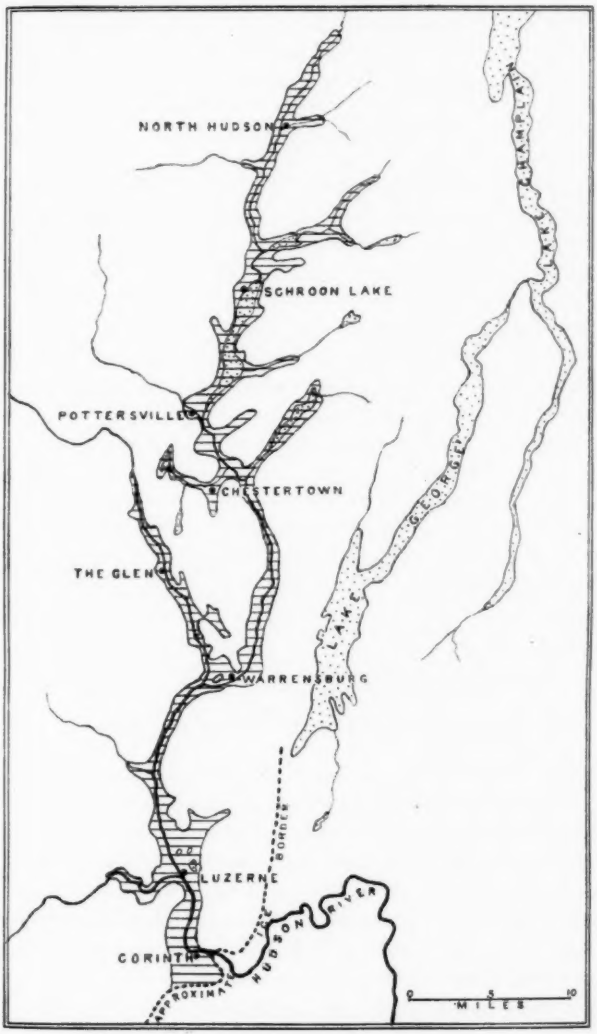

FIGURE 1.—*Map showing Extent of Glacial Lake Warrensburg*

The lined area indicates the location of the lake in southeastern Adirondack region of New York State.

ward in the Hudson Valley from Warrensburg; 4 miles westward from Starbuckville and over the site of Loon Lake; 8 miles northeastward from South Horicon and over the site of Brant Lake; and 9 miles northeastward up the valley of Paradox Creek and over the site of Paradox Lake.

The Lake Deposits

Evidence for the former existence of the body of water here called Lake Warrensburg consists in the presence of more or less extensive and perfectly preserved, crudely stratified, delta deposits and sand and gravel plains or flats. The surfaces of these deposits are remarkably free from boulders and they are often pitted with kettle holes. The deposits lie at concordant altitudes (allowing for postglacial tilting). The numerous delta terraces and sand plains increase in altitude from less than 700 feet on the south to over 980 feet on the north, a few of the finest examples being located as follows: along the railroad southwest to southeast of Corinth (680 feet); south of Lake Luzerne (720 feet); one mile south of Stony Creek Station (740 feet); general vicinity of Warrensburg (760 + feet); 5 miles north of Warrensburg, on west side of Schroon River (780 + feet); north-northwest of South Horicon (840 + feet); vicinity of Pottersville (860 + feet); north of Schroon Lake village (900 + feet); North Hudson (960 feet), and 2 miles southwest of Deadwater Pond (980 + feet). From Schroon Lake northward through the Schroon Valley for 15 miles there is a wonderful exhibition of delta terraces and sand plains in almost continuous succession.

Relation to Glacial Lake Schoharie

According to Fairchild,[10] who has described the succession of glacial lakes in the Mohawk Valley, a long, narrow branch of his large Schoharie Lake extended through the Sacandaga and Hudson valleys of the Luzerne Quadrangle. The lowest level Schoharie waters at the latitude of Little Falls stood at about the present 880-foot level. Allowing for postglacial uplift toward the north, a branch of Schoharie Lake, even at its lowest water stage, must have stood fully as high as the present 900-foot level in the Hudson Valley of the southern part of the Luzerne Quadrangle and considerably higher than that in its northern part. The present writer does not believe that such high-level waters stood in this part of the Hudson Valley, because he was unable to find anything like well defined, persistent lake deposits at any such level in the valley, the lake deposits actually being nearly 200 feet lower.

Relation to Sacandaga Glacial Lake

The arm of Lake Warrensburg which extended several miles westward up the Sacandaga Valley certainly did not reach beyond Conklingville, because westward from that village distinct delta deposits and small sand flats lie at altitudes of 770 to 780 feet, and even the present flood-plain of the river lies at too high a level (740 ± feet) to correlate with the Lake Warrensburg deposits. The standing water in which these higher level deposits accumulated formed part of Brigham's Sacandaga Lake,[11] which flowed into Fairchild's Amsterdam Lake through a pass at 760 feet a few miles southeast of Gloversville. Sacandaga Lake occupied the broad lowland between Northville and Broadalbin and reached, in the form of a narrow arm, northeastward for 15 miles, to the vicinity of Conklingville, where the lake waters were retained by the wall of the retreating glacier. Sacandaga Lake was, therefore, an earlier formed, distinctly higher-level lake than Lake Warrensburg. Removal of the ice-dam allowed the Sacandaga Lake waters to flow eastward into the lower level Lake Warrensburg.

Position of the retaining Ice-front

It is believed that the level of Lake Warrensburg was maintained by the wall of the retreating Hudsonian ice-lobe, which extended across (and blockaded) the Hudson Valley in the general vicinity of Corinth, for most of the time to the south and east of that village site. The outlet of the lake was between the ice (lying on the general lowland) and the steep front of the southeastern Adirondack highland near South Corinth, where there is a pass (see Fairchild,[10] page 36) cut by a stream of large volume. After the outlet was cut down to the 636-foot level at South Corinth, the ice blockade across the Hudson Valley east of Corinth disappeared and Lake Warrensburg was soon lowered to extinction, because the new outlet east of Corinth was much lower than that at South Corinth.

According to Stoller,[7] "as the ice-sheet continued to withdraw to the north, a lake (Lake Corinth) developed, bounded by the belt of moraine on the south and having the ice-front as its northern margin." According to Fairchild,[10] the Adirondack region, including the Hudson-Schroon valleys from Corinth north, was free from the ice while a great lobe of ice still occupied the Champlain Valley and part of the main Hudson Valley. Much study of the southern Adirondack region has convinced the writer that the evidence presented by Fairchild is essentially correct.

This view is substantiated locally not only by the several sets of well preserved glacial striæ pointnig west a few miles east of Corinth, but also by the accumulation of heavy morainic deposits at the base of the high, steep mountain face west of Corinth and South Corinth.

Among the factors of the physical setting unusually favorable to the development and maintenance of ice-dammed Lake Warrensburg were (1) the gently south-sloping, long, narrow Hudson-Schroon Valley, and (2) the great, thick Hudsonian ice-lobe, which held its position against the high, steep face of the southeastern Adirondack highland. Even with considerable melting of the ice and with somewhat of retreat, the general high level of the lake was maintained long enough for the numerous debris-laden tributary streams to produce the deposits in the unusually narrow body of water in a relatively short time.

Post-glacial Tilting and Erosion

It is a well known fact that during the closing stages of the Quaternary Ice Age and just afterward northern New York, including the site of Lake Warrensburg, lay hundreds of feet below its present altitude. Postglacial, differential uplift, with greater elevation toward the north, has brought the land to its present altitude. The differential character of the uplift is clearly recorded by the delta terraces and sand flats deposited in Lake Warrensburg. As already shown, these deposits increase in altitude from south to north (a distance of about 66 miles, airline) from less than 700 feet to nearly 1,000 feet, or at the average rate of about 4.5 feet per mile. The rate of increase seems to be by no means uniform. From near South Corinth to Warrensburg (22 miles) the rate is about 3.6 feet per mile; from Warrensburg to Pottersville (17 miles, airline) the rate is nearly 6 feet per mile; and from Pottersville to Deadwater Pond (27 miles) the rate is about 4.5 feet per mile. These figures are, however, based upon altitudes of the lake beds taken from the topographic maps, which latter are not sufficiently correct for very accurate determinations of the increase in altitude. The higher rate between Warrensburg and Pottersville may possibly in part be interpreted either as indicating water levels at slightly different altitudes or as errors on the maps, but the steady increase in altitude northward of the many well preserved high-level lake beds strongly incline the writer to the view that they were formed in a single body of water, and that postglacial tilting has there been locally in excess of the average rate. The increase in altitude northward of the Lake Warrensburg deposits at a rate higher than that of the lake deposits in the Champlain Valley[12] may be explained

on the basis of earlier removal of the ice-load from the southeastern Adirondack region, with a consequent longer time for postglacial uplift.

Through erosion by the Hudson and Schroon rivers and their tributaries, considerable portions of the Lake Warrensburg deposits have been removed. The deposits commonly have been eroded to depths of from 50 to 200 feet, as, for example, about 200 feet at Luzerne, 150 feet at Warrensburg, and 60 feet at Pottersville. Greater volume of water caused the deeper erosion toward the south.

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EUSTATIC BENCH OF ISLANDS OF THE NORTH PACIFIC[1]

BY CHESTER K. WENTWORTH AND HAROLD S. PALMER

(*Read before the Society December 29, 1924*)

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[1] Manuscript received by the Secretary of the Society March 30, 1925.
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Introduction

Daly[2] has compiled descriptions of raised wave-cut platforms from about thirty places scattered about the world. The present authors have been struck by the fact that a bench from 4 to 12 feet above mean sea-level exists on all of the volcanic islands of the Hawaiian chain, without exception Every island in the chain shows it.

One or the other of us has observed the bench on La Perouse Rock at French Frigates Shoal, Necker Island, Nihoa Island, Kaula Island, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe, and Hawaii. Study of photographs in the files of the Honolulu office of the Hawaiian District of the United States Lighthouse Service indicates that the bench exists on Lehua and Molokini. A photograph, blurred by the motion of the surfboat from which it was taken, suggests that Gardner has the bench. Reliable oral testimony indicates that the bench is to be found on Niihau, and we have also observed the bench on the small islets off the shores of Oahu. Additional evidence of a recent higher stand of the sea is furnished by the emerged masses of reef or of detrital limestone observed on Fanning, Christmas, Jarvis, Washington, Howland, and Baker islands of the Line group.

Shortly before the present paper was submitted in final form for publication, Dr. Wetmore's paper on the bird life of some of the islands in question appeared in the National Geographic Magazine, and the bench on Necker Island is shown in one of the illustrations accompanying this paper.[3] There has also appeared recently a report on the reefs of Samoa, in which a wave-cut bench, now some ten feet above sealevel, has been described.[4]

Description of the eustatic Bench

General features

The bench is best developed on tuff cones, such as those in the Koko Head region at the east end of Oahu. The tuff cones are much younger than the flow lavas that form the main mass of the island, for in places the tuff extends into valleys cut in the lavas. The bench is in general from 10 to 30 feet wide. In places it narrows or tapers out entirely.

[2] R. A. Daly: A recent worldwide sinking of ocean level. Geol. Mag., vol. lvii, no. 672, June, 1920, pp. 246-261; also, A general sinking of sealevel in recent time. Trans. Nat. Acad. Sci., 1920, pp. 246-250.

[3] Alexander Wetmore: Bird life among lava rock and coral sand. National Geographic Magazine, vol. xlviii, no. 1, July, 1925, p. 80.

[4] A. G. Mayor: Structure and ecology of Samoan reefs. Pub. 340, Carnegie Institution of Washington, 1924, pp. 1-2.

Elsewhere it may be as much as 120 feet wide, as in the flow lavas on the west side of Nihoa Island, or even 150 feet wide, as in the tuff on Manana Island, off the east end of Oahu.

The bench ranges in elevation from 4 to 12 feet above mean sealevel. We believe that the bench is in general a little higher on the most exposed

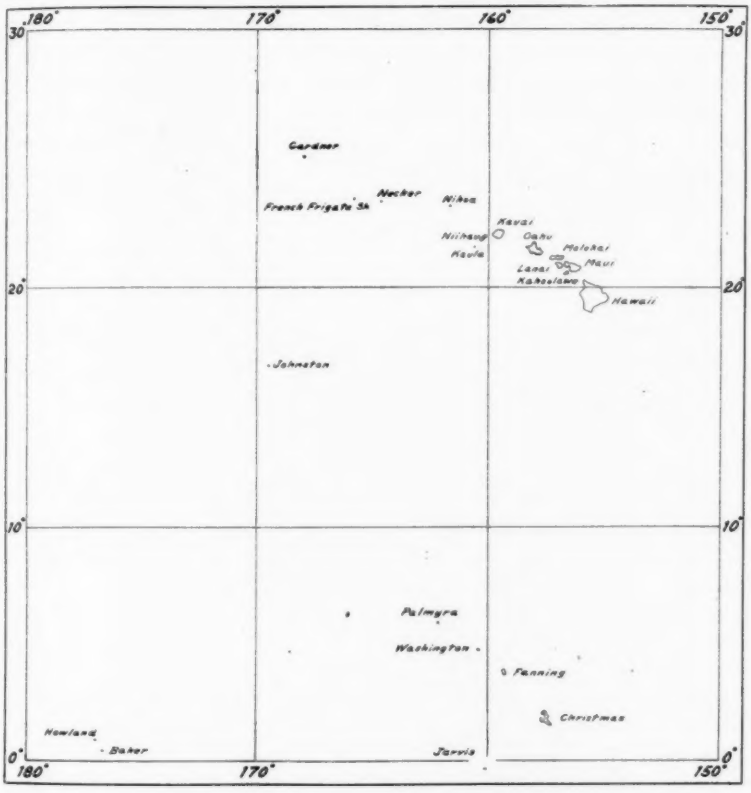

FIGURE 1.—*Map of Portion of North Pacific Ocean*

Showing locations of islands mentioned in the text and including all the high islands within its limits.

parts of promontories and lower along the shores of bays, but no statistical data can be given at this time. At all events, the bench varies considerably in elevation, even in short distances. The variations are so irregular that they can not be ascribed to movements in the lithosphere,

but must be due to original differences in texture or jointing, or both.

The emergence of the bench appears to indicate a negative shift of sealevel of 12 to 15 feet. Ignorance of the depth of effective cutting during the forming of the bench makes closer estimates impossible at present. It does not appear, however, that there has been a shift in the North Pacific region as great as the 20 feet deduced by Daly.[5]

Minor variation of elevation, which is another way of saying "roughness of the bench surfaces," is due in part to lithologic variation, in part to varied inclination of tuff beds or lava-flows, and in part to jointing.

The smoothest bench surface is developed on tuff, a rock more free of joints than most. Absence of joints and the granular texture favor smoothness. Benches cut on basalt flows are commonly rougher, but vary greatly in this respect. Dense flows that have few joints give smoother

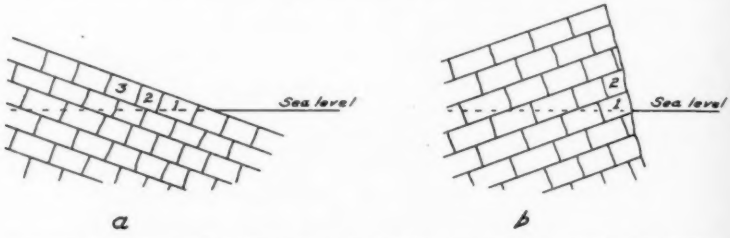

FIGURE 2.—*Sketch illustrating Structure Relations on normal reversed dip Coasts*

benches than do flows of the "slag heap" type, formed by excessive shattering of the rigid lava-crust by the drag of the still fluid interior of the flow.

The normal type of shore structure for volcanic islands is such that the flows strike parallel to the shore and dip seaward, and may be called "normal-dip coasts" (see figure 2). "Reversed-dip coasts," where the strike is parallel to the shore, as before, but the dip is toward the land, are rare, as are also "cross-strike coasts," in which the dip is parallel to the shore.

Cross-strike coasts (figure 3) seem to have rougher bench surfaces than either of the other types. There are also many unexplained irregularities. For example, on the Koko Crater coast, Oahu, there is one stretch of compound bench 400 feet long and 50 to 100 feet wide. Four levels, separated by gently sloping scarps, are clearly recognizable. The scarps are from four inches to a foot and a half high.

[5] Op. cit.

In places where the bench is cut in tuff it may be so level for a considerable area that no point of the tuff surface departs more than four or five inches from a mean level, as indicated by quiet pools of wave-thrown

FIGURE 3.—*Northwest Cape, Necker Island*
View of bench looking southwest along northwest side.

spray. Several such places are to be found on the Koko Crater coast, but the most striking is on Manana (Rabbit) Island, off the east end of Oahu (figure 9).

In some instances such level parts of the bench are bordered on one or more sides by slightly higher masses of tuff and the water pools are maintained at a nearly constant level. No experiments nor critical studies have been made to determine the condition of the rock. We suggest that these "water-level" portions of the bench are due to intensified weathering in the zone extending a few inches above and below the water level of the pool. The combined work of water and air in the zone which is exposed alternately to each seems analogous to the more rapid rotting of poles, piles, and other wood structures at soil or water lines.

If this weathering process be operative, any portions of the wave-cut bench now exposed above sealevel, but in reach of dashing spray and sufficiently inclosed to contain incipient water pools, would become the sites of larger and larger pools, as abrasion followed the "water-level" weathering. This feature has not been observed on basalt benches and the process is believed to have appreciable effects only on the tuff. Since basalt is almost universally cut by joints, it is rare for pools to be held on the basalt benches; the water drains away readily through the joints. Since there is no local water-table in the basalt, there is no such zone of weathering, and consequently no localization of abrasion by wind and spray.

RELATION TO STRUCTURE

That the bench is not of structural origin is shown by the fact that it cuts obliquely across inclined flows of lava and beds of tuff. The most striking evidence of this is at the crater of Puu Pehe, at the south end of the Island of Lanai, where the bench cuts across the axis of the crater rim, with its indipping and outdipping layers. Below the 600-foot high cliffs of the cross-strike west coast of Nihoa are a number of fragments of bench. Their level surfaces truncate the lava-flows, which dip about 10 degrees and also cut across several dikes. The dikes strike northeast and continue vertically to the top of the cliff behind the bench.

Elschner[6] speaks of several levels of terrace, one above the other, on Necker Island. It is true that there are subplane surfaces at higher elevations than the eustatic bench, but they are structural in origin, being determined by the difference in resistance to weathering of the various lava flows. These surfaces dip with the 10 degrees dip of the flows, whereas the level eustatic bench truncates the flows.

It is obvious that most coasts of volcanic islands will be of the normal, or seaward-dipping, type. Reversed-dip coasts are most facilely ex-

[6] Carl Elschner: The Leeward Islands of the Hawaiian group, 68 pages, reprinted from *Sunday Advertiser*, Honolulu, 1915.

plained as due to faulting, but not necessarily most validly. If faulting is infrequent, reversed-dip coasts should be scarce. The greatest amount of bench should be found on coasts of normal dip, because that kind of coast is most common. It is to be noted that when a tuff cone is so reduced that it becomes a crescent with the erstwhile crater forming the concave side, both coasts will be of the normal dipping type, because the layers of the inner part of the crater rim dips toward the center.

In the Hawaiian chain of islands only three reversed-dip coasts are known: parts of the north coast of East Molokai, the north coast of Nihoa, and the south coast of Necker. It should be remembered that Nihoa and Necker are comparable to one another in size, lithology, and exposure. The bench is much more poorly developed on the reversed-dip coasts of each of these islands than on the normal-dip coasts. The bench is also poorly developed on the north coast of East Molokai—a coast of reversed dip. Consideration of the manner in which joint blocks bounded by flow bedding are held together on the two types of coast indicates that erosion of reversed-dip coasts proceeds more slowly than erosion of normal-dip coasts, at least so far as plucking by wave suction is concerned. Figure 2*a* represents a normal-dip coast. Suppose that the waves have removed block number 1; then block 2 becomes unsupported on the seaward side and especially liable to be removed in turn, thus exposing block 3, and so on. Figure 2*b* represents a reversed-dip coast. Suppose the waves have plucked out block 1. Block 2 and those above it will fall immediately, but the other blocks farther inland will be wedged together and will be able to resist plucking rather effectively. A similar conclusion has been reached by Lake.[7]

RELATION TO COASTAL EXPOSURE

Since northeasterly trade winds prevail in the Hawaiian region, it might seem likely that northeast exposures would control the distribution of the bench. Necker and Nihoa Islands are alike in being isolated and built of flow lavas, and they are of comparable size. On Necker the bench is far better developed on the windward than on the leeward side; on Nihoa the reverse is true.

Kaula, Lehua, and Molokini are of closely comparable size. Kaula is fully exposed to the wind; Lehua is somewhat sheltered. Molokini is decidedly sheltered, as it is only three or four miles down the wind from the big mass of East Maui (Haleakala). All three are fragments of tuff cones. On Kaula and Molokini there is almost continuous bench on the

[7] Philip Lake: Physical geography, p. 212. Cambridge, 1919.

windward side and none on the leeward side. Similarly, Lehua has bench on much of the windward side, but none on the leeward side.

In the case of the three tuff islands, there seems to be a correlation, but with the two lava-flow islands there is no correlation of bench development with exposure to prevailing winds. However, there are not enough examples available to make a statistical study possible.

It is evident that configuration of the adjacent submarine surface, with its effect on waves and currents and accumulation of debris, and the details of prevailing wind movements must be closely studied before conclusions are reached as to relative rigor of abrasive processes.

Another consideration is that in those situations where the bench was extensively developed during the pre-shift stand of the sea a similar strong wave action is likely to have destroyed the bench before the present time. Such preponderant tendency to destruction is believed to be favored by the following factors:

1. Strong wave action develops a bench at greater depths than weak. Such a bench might even be low enough so as not to have emerged at the time of shift and hence have been far more quickly removed than a higher bench.

2. The linear rate of marine transgression is progressively reduced as the bench becomes wider. The capacity of strong wave action to cut away an existing bench and reach the same stage of slow attack on a high cliff is thought to be greater than that of weaker wave action, each considered with respect to a bench cut by its own attack. This factor would favor the more general preservation of benches in the sheltered situations.

OTHER EVIDENCES OF RECENT STRANDLINE SHIFT

Emergence of the land, either by rise of land or lowering of water level, is shown by three classes of evidence. The first class comprises the exposure, at elevations now well above sealevel, of features cut by marine action, notably by wave erosion, such as the bench under discussion, sea cliffs, caves, and stacks. The second class includes similar exposure of features due to marine deposition, such as bars, offshore beaches, and coralline reefs. The third class comprises drainage changes due to changes of baselevel. No drainage changes which could be correlated with the shift under discussion have been noted in the Hawaiian region, perhaps because of the shortness and steepness of the stream courses. Numerous valley mouths have been drowned, which indicates a shift in the other direction, evidently before the emergence of the eustatic bench.

There is invariably a pronounced sea-cliff behind the eustatic bench of

the Hawaiian region, except where tiny islets have been completely truncated by the bench. Associated with the eustatic bench are sea-caves and arches in situations now a little too high to be effectively attacked. In a number of places are stacks which are separated from the mainland by a considerable expanse of more or less continuous bench (see figures 13 and 14).

Many of the valleys of Oahu have deep alluvial fills, so steep that they may better be called constricted alluvial fans than floodplains. Many of these fans terminate in scarps 5 to 15 feet high and as steep as the angle of repose of the coarse, unconsolidated material of which they are made. The drowning of valley mouths indicates that formerly Oahu stood several hundred feet higher than it does now, as did others of the islands. Presumably the alluvial fill was deposited during the time of high position. Subsequently the sea rose higher than its present level and stood there long enough for the scarps to be cut. Though the material of the alluvial fill is now weak and rotten in large part because of deep weathering, it is probable that it was then fresher and withstood the attack of the relatively weak waves of the narrow estuaries. The time involved seems comparable to the time involved in cutting the eustatic bench in tuff or lava.

On the south coast of Oahu, from Makapuu to Barber's Point, there is a great deal of raised reef. The maximum elevation of undoubted reef is about 35 feet, and a considerable part of the reef formations of Oahu is too high to be associated definitely with the eustatic shift under discussion. Material which has been described by laymen as reef at higher elevations than 35 feet has always on examination turned out to be either lower than was thought or to be composed of either wind-blown calcareous sand or of excessive accumulations of calcium carbonate by percolating water. Oahu has a better development of both raised reef and living reef than any of the other islands of the Hawaiian group.

In at least one place on the Koko Head coast of Oahu is a mass of coral and other calcareous debris which appears to have been deposited during a higher sealevel and in association with the cutting of the bench.

The four southern Line Islands have raised formations of reef or detrital limestone which reach a maximum elevation of about 12 feet above sealevel. Since at the present time similar reefs are being built in situations where they are awash at low tide, it appears that a shift in sealevel of about 12 feet is indicated, and these probably give the most accurate single measure available.

CAUSES OF THE STRANDLINE SHIFT

Changes in the relative elevation of land and sea of the sort in question may be due to uplift of the land, to withdrawal of the sea, or both. For any restricted locality it is usually impossible to determine which has taken place. The emergence indicated by the features described above is believed to be due to a lowering of the level of the sea. Uniform uplift without appreciable tilting of an area of three million square miles, such as that represented by the Leeward, Hawaiian, and Line Islands, seems highly improbable. Furthermore, the interpretation of eustatic shift falls in line with a growing mass of evidence for similar lowering of sealevel along all the coasts of the world, as pointed out by Daly and others.

No evidence is afforded by the field relations in Hawaii bearing on the cause of such a lowering of sealevel, and the larger problem of such world-wide oscillations of sealevel lies beyond the scope of the present descriptive paper.

AGE OF THE SHIFT

No means is at hand for fixing the date of the shift with great accuracy. The emergence postdates the latest secondary eruptions on Oahu, for the youngest tuff craters in the Koko region carry the exposed wave cut bench around their margins. These craters are enormously younger than the Salt Lake craters, which are associated with terraces and other physiographic features believed to have been formed in Pleistocene time. The later Koko region craters are estimated to be not over twenty thousand years old and may be no more than five, or possibly even one, thousand years old, and an upper limit is thus set for the age of the eustatic shift. Certain coasts on Hawaii formed of prehistoric flows from Kilauea and Mauna Loa do not show the bench and the shift thus appears to be definitely prehistoric.

Detailed Accounts of Island Benches

TABULATION OF THE ISLANDS

The following table indicates the islands visited by each of the authors:

Island.	Visited by Wentworth.	Visited by Palmer.
Gardner		
French Frigates Shoal		*
Johnston		*
Necker		*
Nihoa		*
Kaula		*
Niihau		
Lehua		
Kauai		*
Oahu	*	*
Molokai	*	*
Maui	*	*
Lanai	*	*
Kahoolawe	*	
Molokini		
Hawaii	*	*
Palmyra	*	
Washington	*	
Fanning	*	
Christmas	*	
Jarvis	*	
Howland		
Baker		

GARDNER ISLAND

Gardner (Gardiner) Island is a small rocky islet in latitude 25° 01′ north, longitude 167° 59′ west, with an elevation of 170 feet. A smaller rock is close to its southwesterly shore. A reef extends about one-half mile from the smaller rock. A bank, with 17 to 20 fathoms, extends about 5 miles northwest, northeast, and southeast and 10 to 12 miles southwest.[8]

Rock specimens collected on Gardner by the members of Trip B of the 1923 Tanager Expedition are all basalt. Landing was said to be difficult. The fact that landing was at all possible suggests the existence of some of the bench on this island. A photograph in the Bishop Museum collection (number 10094) is blurred by movement of the small boat from which it was taken, but suggests the presence of a bench. A bench was

[8] Coast Pilot notes on Hawaiian Islands. U. S. C. & G. S., 2 ed., 1919, p. 51.

noted by Dr. A. Wetmore, of the United States Biological Survey, who was a member of the same party. He reports that it was best developed on the northeast side of the island.

LA PEROUSE ROCK, FRENCH FRIGATES SHOAL

French Frigates Shoal is a crescent-shaped atoll, formed by two arcs of reef of different curvature. In the area included by the two reefs are several small, low sand islands. La Perouse Rock lies midway between the ends of the crescent and to leeward of the leeward and less sharply curving line of reef. It is 350 feet long from northwest to southeast, 40 to 80 feet wide, and 120 feet high. It is composed solely of basalt flows which dip gently to the northwest. Landing was made on a small fragment of bench on the southwest side of the rock by the members of Trip C of the 1923 Tanager Expedition. The maximum width is 10 or 12 feet and it extends some 60 feet. It is 5 to 8 feet above sealevel. Mr. A. E. Arledge, formerly Superintendent of the Hawaiian Lighthouse District, said that he landed at the northwest end of the rock on the bench and traversed the bench for half the length of the northeast side, to a point where he was able to ascend to the summit. It is possible that he landed on a structural bench developed on a particularly resistant flow and followed the surface of this flow. Two hundred feet northwest of this islet is a still smaller one, with a flat top 30 by 70 feet and 8 feet high. This looks to be a bit of high bench, but it may be of structural origin. The bench on the southwest side of the main islet seems not to be structural, as a flow surface may be followed upward from the bench.

JOHNSTON ISLAND

Indurated calcareous conglomerate and sandstone lie 4 feet above mean tide on Johnston. No undoubted emerged reef rock was seen during a four hours' visit ashore.

NECKER ISLAND

Necker Island has a maximum height of 276 feet and an area of 41 acres. It is about 4,000 feet long east and west and averages 400 or 500 feet in width. From the west end of the island a peninsula, "Northwest Cape," extends north-northeast, giving the island the shape of an "L." A bank surrounds the island, giving depths of 14 fathoms and upward for 5 to 30 miles distance. The rocks are all basaltic. The flows dip 11 degrees northeast and strike north 85 degrees west. A number of vertical dikes bear about northeast-southwest. Some of the flows and

dikes contain megascopic olivine and in a few augite can be seen. There are no pyroclastic rocks.

In the bay between Northwest Cape and the main branch of the island there is considerable actively growing reef, which partly breaks the force of the waves on this side. A wave-cut bench extends along most of both the east and west shores (figure 3) of Northwest Cape and adjacent shores of the main island and was noted in several patches on other parts of the shore. Along the shores of the more protected bay at the north the bench is about 4 feet above sealevel, whereas it is about 8 feet high on the exposed west end of the main island.

NIHOA ISLAND

Nihoa Island (also called Modu Manu, Moku Manu, and Bird Island) has an area of 127 acres and a maximum elevation (Millers Peak) of 895 feet. The west, north, east, and southeast sides are nearly vertical, large parts being 600 feet or more high. These shores are also nearly straight. The water parting is everywhere near these precipices, so that 90 per cent of the surface drains southward by seven valleys, with slopes that average 25 degrees. The south shore is formed by Adams Bay, which is of rather irregular outline, due to the alternation of valleys and spurs. The extreme length of the island is 4,800 feet and the average width about 1,400 feet. The rocks are all basaltic. Numerous dikes bearing north 60 degrees east cut the flows, which strike north 55 degrees west and dip 10 degrees southeast. No pyroclastic rocks were seen, though a lookout was kept for them. Nihoa is on a bank with 20 to 40 fathoms of water.

In general the shores of Nihoa either have a distinct, undoubted bench four to eight feet above sealevel or the bench is entirely lacking. The bench extends along most of the shores on the south, or Adams Bay, side, but is found only as short stretches on the other sides of the island.

KAULA ISLET

Kaula Islet, or Kaula Rock, is a fragment of the rim of an extinct tuff crater. It is about 2,000 feet long and its height is probably about 550 feet. As seen from the bridge of the *Tanager* during a circumnavigation, the islet appears to consist solely of tuff, which is in all probability of basaltic composition. A photograph by the Naval Air Force shows the bench extending along more than half of the inner curve of the crescent. Another photograph of the outer curve shows no bench. Deep, reefless waters surround Kaula.

Mr. R. R. Tinkham, Superintendent of the Hawaiian Lighthouse District, stated that the bench extends the full length of the inner curve and supported his statement with excellent photographs.

NIIHAU

Until recently, little information has been available concerning Niihau because of the policy of the owners of the island. Mr. Charles Gay, who lived for many years on Niihau, states that much of the southeast coast is precipitous, but that on the gentler northwest coast and on the southwest end of the island there are numerous fragments of the bench cut in flow lavas. Similar testimony comes from Mr. N. E. A. Hinds,[9] who recently studied the geology of Kauai and Niihau. He finds the bench clearly developed on Niihau, but the evidence of emergence is less abundant than on Kauai.

LEHUA

Lehua is a remnant of a small, parasitic crater at the north end of Niihau. According to the Lighthouse Service, half of the crater rim has been destroyed and the north half of the windward side, which is also the concave side, has a well-developed bench, as is usual on tuff shores. The photographs at the Lighthouse Service office show the bench unequivocably. It cuts across ash beds that dip seaward about 25 degrees and appears to be 25 to 100 feet wide. At the back of the bench is the appropriate wave-cut cliff.

KAUAI

On a brief visit to Kauai in 1924, the bench was observed at a number of points on the north coast west of Hanalei Bay and at Kawai Point, south of Nawiliwili Bay, on the east coast. The same feature is found rather broadly developed at the "Spouting Horn," east of Lawai Bay, on the south coast. Hinds[10] found abundant evidence of emergence on Kauai, which he plans to describe in detail in his forthcoming report. The amount of emergence indicated by the bench and other features agrees with that found by the writers on other islands.

OAHU

On the island of Oahu the bench is best developed in the southeast portion, extending along the coast from Pearl Harbor eastward to Makapuu Head and thence northwestward to Mokapu Peninsula. In the vicinity

[9] N. E. A. Hinds: Private communication.
[10] N. E. A. Hinds: Private communication.

of Pearl Harbor and the Salt Lake tuff craters are a number of localities where low sea-cliffs have been cut in positions slightly higher than are now accessible to the waves. Certain coral formations in this vicinity now somewhat above sealevel probably date from the same time as the cliffs, though other much higher and older emerged reefs are also found in the region. Fragments of bench partially mantled by beach sediments are found along the seaward margin of Diamond Head and the same are imperfectly shown on Black Point. Round the entire margin of the Koko Head Peninsula it is exceptionally well developed in the tuff of which the peninsula is exclusively composed (figure 4). The best single

FIGURE 4.—*View of eustatic Bench on Coast of Koko Head, Oahu*

expanse is found round the shore of Hanauma Bay, where the bench is broken in but two or three places in over a mile, is from 5 to 10 feet above sealevel, and ranges from 10 to 50 feet wide (see figures 5 to 7).

At least half of the perimeter of Manana Island just north of Makapuu Head is marked by an emerged wave-cut bench ranging from 5 to 15 feet above sealevel. The east shore of this island is for the most part very precipitous, with deep water at the foot of the cliff. At the site of a former crater throat the concentrically dipping beds have been truncated by a superb bench 150 feet wide and 400 feet long. The structure has apparently favored deeper cutting inland and the inclosure of a spray-fed pool which has now extended itself by water-level weathering

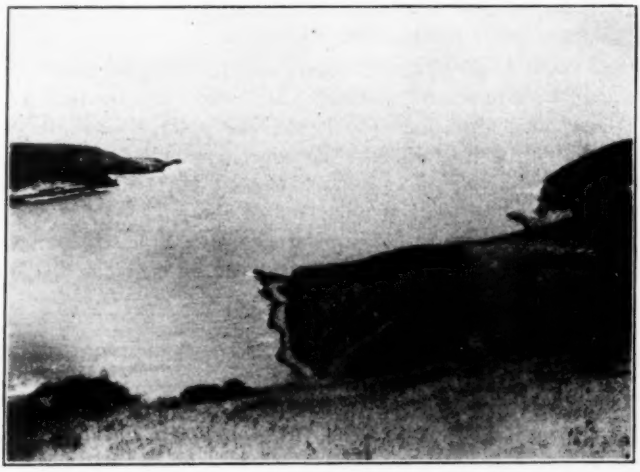

FIGURE 5.—*Eustatic Bench on both Sides of Hanauma Bay*
View from flank of Koko Head summit, Oahu.

FIGURE 6.—*Near View of Bench on east Shore of Hanauma Bay, Oahu*
The bench is here cut across the edges of tuff beds, dipping 20 to 25 degrees.

FIGURE 7.—*Small Cove in Bench on west Side of Hanauma Bay, Oahu*

This level floor has been produced in part by "water-level" weathering, as described in the text.

FIGURE 8.—*View looking eastward along south Coast of Manana Island, Oahu*

The bench here shows far more vigorous erosion and less etching due to weathering than those in the Hanauma Bay region.

FIGURE 9.—*View of "water-level" Pool on Bench on the east Coast of Manana Island*

This patch of bench is developed across the concentric indipping tuff beds of one of the volcanic vents responsible for the building of the island and is a remarkable example of wave-work in a locally favorable situation.

FIGURE 10.—*View of west Coast of Lanai*

The view is taken looking north from a point south of Kaumalapau Harbor. Eustatic bench is shown broadly developed at the foot of the cliffs in the middle distance.

over the whole area of the bench. Probably less than 2 per cent of the area differs from the mean level by over a foot (figures 8 and 9).

The bench is clearly developed on the more protected parts of Ulupau crater, whereas the exposed parts have steep cliffs flanked by deeper water. A fine bench may be seen surrounding Moku Manu Islands one mile north of Ulupau, but these have not been visited. The bench has been identified on the coast northeast of Waialua, near Makaha, and southeast of Nanakuli. Truncated alluvial deposits along many parts of the windward coast and west of Waialua also indicate wave-work at a slightly higher level than is possible at present.

MOLOKAI

The bench is fairly well developed on all parts of the Molokai shore which were visited. These include the westernmost ten miles of the south coast, short stretches of the west and north coasts as far around as Waikolu and the vicinity of Kaunakakai, Kamalo, Pukoo, and Halawa. The north coast from Halawa to Waikolu was skirted in a small boat. Only small fragments of bench are found at places flanking the high cliff of this coast. Much of the south coast of Molokai now consists of a narrow alluvial plain, less than 10 feet above sealevel, which extends inland along the gulch channels and merges with the stream grades. Between the streams the sloping spurs are commonly truncated by old sea-cliffs 10 to 50 feet in height, and the eustatic bench which is believed to be continuous is veneered by the alluvium of the plain. Toward the west end the alluvial plain becomes narrower, and well defined wave-cut benches were observed at a number of places at elevations of 6 to 10 feet above sealevel. Considerable masses of calcareous sandstone were noted in situations too high to have been formed under existing conditions.

MAUI

The bench has been observed at a number of places on the shores of West Maui and on headlands west of Maliko Bay on East Maui. Bench is developed at a number of places on the south shore of West Maui, from MacGregor's Landing to Lahaina, and in a few places it truncates lava-flows that dip about 15 degrees seaward (figures 11 and 12).

LANAI

The Island of Lanai shows on its west and southwest coasts one of the best examples of bench cut in lava rock seen by the writers. It is probable that this impression is due in part to the somewhat detailed examina-

FIGURE 11.—*View of Bench looking west past Mouth of Maliko Gulch, East Maui*
In the distance are the slopes of West Maui. Bench is cut in basalt.

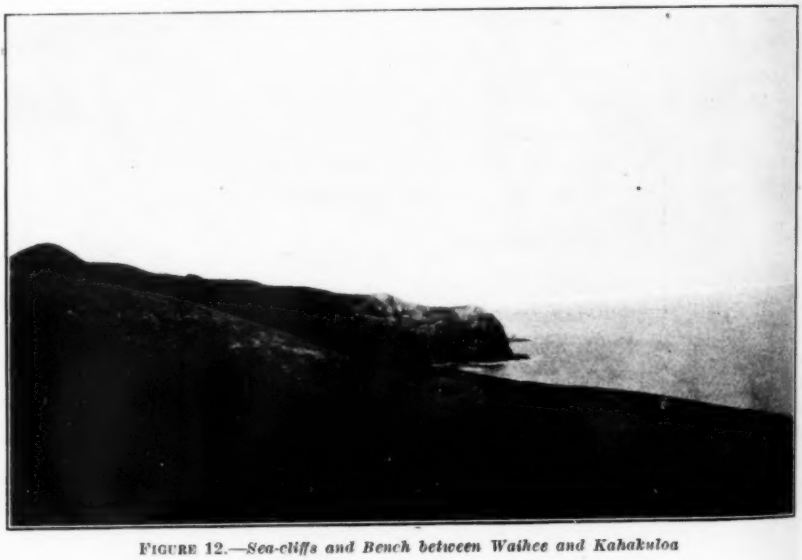

FIGURE 12.—*Sea-cliffs and Bench between Waihee and Kahakuloa*
View is on northeast side of West Maui. The rock is basalt.

tion made of this island, and that similar conditions will be found elsewhere by students making more extended studies on other islands of the group. From the northwest point of the island to Kaumalapau Harbor (figure 10) and along much of the south coast east and west of Manele is a succession of alternating bays and headlands. The wave-cut bench is present on the majority of the headlands at 8 to 10 feet above sealevel and has associated with it a fine series of sea-caves and stacks produced at the time of higher sealevel (see figures 13 and 14). The bays are commonly fringed by coarse gravel beaches merging inland to poorly assorted alluvium from the gulches. Commonly the bench is not over 10 or 15 feet wide, but in places the gently dipping lava flows have been truncated by the abrasive action of the waves over areas 100 or more feet in width and twice as long.

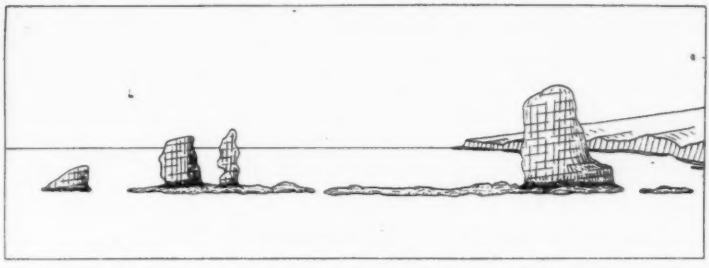

FIGURE 13.—*Eustatic Bench surrounding wave-cut Stacks*

The location is on the west coast of Lanai, south of Honopu Bay. The stacks are known locally as the "Five Sisters."

South of Kaumalapau Harbor is a straight section of coast consisting of an almost vertical cliff ranging from 200 to 1,000 feet in height. This cliff is believed to be due to faulting. No good bench is known along it, though a boulder beach 10 or 20 feet wide lies at its foot and is accordant with present sealevel.

The north, northeast, and east coasts of Lanai are low and formed largely of recent alluvial and marine sediments. Detrital limestone formations of marine origin extend to 10 feet above sealevel at a few points, and some of the spurs are truncated by old wave-cut cliffs somewhat back from the present shore.

KAHOOLAWE

A well defined wave-cut bench about 10 feet above sealevel was seen at the boat landing near the east end of the north coast of Kahoolawe.

Similar benches were seen on adjacent parts of the coast from the boat. Fragments of bench here and there around the margin of the deep indentation on the south coast were seen from the highland to the north.

MOLOKINI

Molokini lies between East Maui and Kahoolawe and is a fragment of a tuff crater rim. The concave side faces west-southwest, according to the Lighthouse Service, though the Coast Pilot says it faces northwest. Statements by the Lighthouse Service officials, supported by excellent

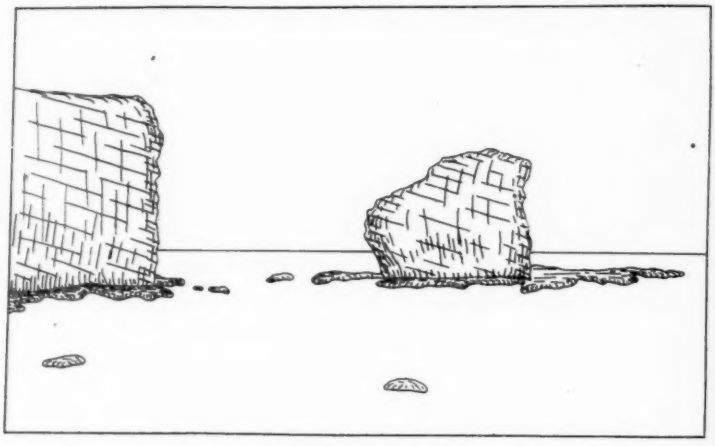

FIGURE 14.—*Puu Pehe*

This shows a wave-cut stack surrounded by eustatic bench, near Manele, on the south coast of Lanai.

photographs, indicate that bench is well developed along the whole of the convex, or windward, side of the island.

HAWAII

No detailed study of the Hawaii coast has been made by either of the authors. When passing the east coast of Hawaii north of Hilo the bench was seen at various points, but the precise localities were not recorded. The peninsula pierced by Onomea Arch has at its outer end a distinct bench which extends inland with progressively lesser widths. Messrs. Dranga and Thaanum[11] report that there is no bench on the coasts formed by Mauna Loa or Kilauea lavas, except possibly at Ka Lae, the southern

[11] Oral communication.

point of the island. According to them, the bench is common along the Mauna Kea coasts, but they are not informed concerning the Kohala coast. There is uncertainty concerning the Hualalai coast. It seems probable that appreciable volcanic activity from Mauna Kea and Kohala ceased before the time the bench was cut, but that Mauna Loa and Kilauea certainly, and Hualalai possibly, have covered the bench, supposing it to have existed, with more recent lavas.

PALMYRA

No evidence of emergence was found on this island, and it is believed that it has been developed wholly since the shift of sealevel took place, and would therefore not be expected to carry a bench or emerged reefs or detrital formations.

WASHINGTON

Emerged masses of reef rock were seen at a few places on the shores of Washington Island, but none was observed at elevations clearly indicating emergence as great in amount as that shown on some of the other islands. It is believed, however, that such would be revealed by sufficiently detailed study, since the general elevation of the island and the present complete inclosure and freshened condition of the lagoon indicate very decisive shift of the strandline. The fresh-water lake and peat bog now occupying the site of the former lagoon have been described elsewhere.[12]

FANNING

No emerged masses of undoubted reef rock in place were seen during two one-day visits to Fanning Island. At a number of places detrital limestone formations were observed at 3 or 4 feet above sealevel, which appeared to indicate emergence, and it seems probable that Fanning has experienced a history similar to that of adjacent islands.

CHRISTMAS

Great masses of deeply weathered coral reef rock and detrital limestone are found at a number of places in the interior of Christmas Island at an elevation of about 10 or 11 feet above sealevel. The ancient lagoon has been converted by withdrawal of the sea into a large number of intensely salt and very shallow lakes. The irregular sporadic distribution of these water bodies can not be satisfactorily explained otherwise than as the residual pools of the once continuous and deeper central lagoon.

[12] Chester K. Wentworth: Geology of the Line Islands. (In press.) Bishop Museum, 1925.

The margins of the old lagoon are rather clearly indicated in the line between the lake-studded flat and the slightly higher rimland of the island.

JARVIS

Jarvis Island is the only one of the Line Group which has a "dry lagoon" and furnishes clear topographic evidence of emergence. Additional indication of such a shift of the strandline is contained in the masses of emerged reef rock and detrital limestone which are found at a number of places on the island. No opportunity to measure the exact amount of emergence was found on Jarvis Island.

HOWLAND AND BAKER

We are indebted to Dr. T. A. Jaggar,[13] of the Hawaiian Volcano Observatory, for the following information concerning these islands: The west, or leeward, sides are about 20 feet high and the east side of each about half as high. Old cemented coral conglomerate is found near the top of each. So far as can be judged from Dr. Jaggar's description and without personal observation, there is a greater similarity between these two islands and Jarvis than with any others of the Line Group and, as pointed out by Jaggar, clear evidence of emergence amounting to somewhat less than 20 feet.

[13] T. A. Jaggar: Personal communication.

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BASIC DIKE INJECTIONS IN MAGMATIC VEIN SEQUENCES[1]

BY J. E. SPURR

(*Read before the Society December 31, 1924*)

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ZONAL THEORY OF ORE DEPOSITION

In 1907[2] I presented the "Zonal Theory" of ore deposition in a paper, the conclusion of which was as follows:

"Summing up, this theory proposes that metalliferous fluids, from which most ore deposits are precipitated, are extreme differentiation phases of rock magmas; that most ore deposits and 'mineral veins,' as a class, represent one

[1] Manuscript received by the Secretary of the Society February 16, 1925.
[2] Econ. Geol., vol. II, Dec. 8, 1907.

or the other of the extreme products of magmatic differentiation; and that the most striking chemical differences between ore deposits is due (in the more important class representing the siliceous extreme) to successive precipitation in theoretically vertical zones, as the fluid migrates toward the surface, and with diminishing heat achieves more and more mature crystallization."

I defined the principal zones as: 1, the pegmatite zone, containing tin, tungsten, molybdenum, etcetera; 2, the gold quartz-auriferous pyrite zone; 3, the copper zone; 4, the lead-zinc zone; 5, the silver zone with much gold; 6, the earthy gangue zone. In 1912[3] I modified the column as follows: 1, the pegmatite zone, containing tin, tungsten, molybdenum, etcetera; 2, the gold quartz-auriferous pyrite zone; 3, the copper zone; 4, the zone of auriferous arsenopyrite and argentiferous pyrite; 5, the zinc zone; 6, the lead zone; 7, the silver zone with much gold. In my book on "The Ore Magmas" I adhered to the last-named system for the intermediate magma provinces, but presented different schemes for the basic magma provinces and for the very siliceous magma provinces.[4]

Since 1907 a great deal of evidence has been brought forward by many geologists as to the existence of these successive zones, and in English geological writings the subject has been recently summarized also by Kemp,[5] Rastall,[6] and Emmons.[7]

In French, De Launay[8] in 1913 elaborated much on the vertical zonal arrangement of ores, but without, so far as I can discover, assigning to different temperatures a major rôle in their fixation, but rather different degrees of transport by "agents mineralisateurs." Kemp, Rastall, Maclaren, Emmons, and others, however, have essentially agreed with my belief that the observed successive zones were mainly due to progressively diminishing temperature upward and outward from an igneous focus of heat.

Also, in 1907 and at many times thereafter, I have shown that the successive stages of ore injection in given mineral districts often illustrate

[3] Econ. Geol., vol. vii, no. 5, Aug., 1912.

[4]

Basic magma	*Intermediate magma*	*Siliceous magma*
Chromium	Molybdenum	Molybdenum
Platinum	Tungsten	Tin
Nickel	Gold	Tungsten
	Copper	
	(Silver)	
	Zinc	
	Lead	
	(Silver)	

[5] Bull. Geol. Soc. Am., 1922, vol. 33, pp. 231-250.
[6] Econ. Geol., vol. xviii, no. 2, 1923.
[7] Trans. An. Inst. Min. Eng., Feb., 1924.
[8] Traité de Metallogenie, 1913.

the same zonal arrangement, the cooler metal zones normally migrating downward, with the dropping of the isogeotherms as cooling progressed, so that they were superimposed upon one another, often in the same fissure. I do not recall that anyone else has taken up the same fruitful line of study.

Temperature of Wall Rocks

I have outlined the above merely by way of introduction and to remind those not thoroughly familiar with the literature. Although these successive zonings are now well recognized, neither they nor the causes which result in the final emplacement of certain metals in a certain place are yet thoroughly understood. The point of view of De Launay regarding the relative potency, as carriers, of volatile magma components will doubtless have to be taken into consideration, and I have followed the same line of thought in part in the discussion of zoning in "The Ore Magmas;" and there are other laws to be considered as well; but it is, nevertheless, probably true that temperature is the chief controlling factor in the differentiation of these metal zones. Granted that this is true, I wish to consider what this implies as to the temperature of the wall rocks of the metallic lodes in question. Let us take the upward and outward succession of metals in Cornwall, for example, where with increasing distance from the granite focus we have successively tungsten, tin, copper, zinc, lead, and silver, the zones overlapping. According to the general conclusions reached, the temperature of the wall rocks in the tungsten-tin zones must have been too high to bring about the crystallization or freezing of the copper, zinc, lead, and silver ores; but the next outer shell of wall rock was below the freezing temperature of the copper ores, but not cool enough to arrest the zinc, lead, and silver ores, while adjacent outer shells were at a lower temperature than that at which these last-named metals consolidated. A close and delicate connection between freezing temperatures of metal zones and the temperatures of wall rocks is thus to be concluded. Since the tin-tungsten ores are in part pegmatitic, and the temperature of pegmatites is commonly accepted as not much below 575 degrees, the wall rocks of the tin-tungsten lodes will have been a little cooler than this figure, but only a little cooler, or they would have arrested the copper ores, whose deposition followed closely on that of the tin-tungsten ores. If, now, we assume that the temperature of the copper crystallization is around 500 degrees centigrade, then the wall rocks in the copper zone must have been cooler than this, but not cool enough to have brought about the consolidation of the zinc-lead-silver ores, which

crystallized in a still outer shell. It would thus appear that where distinct zoning, or successive injection in one zone according to the succession shown in typical zonal arrangements, occurs, the wall rock of lodes must have been of nearly the same temperature as the consolidating point of the metals which characterize the lodes. It also follows that well differentiated lodes, showing very predominantly one metal or another, will occur only in rocks which had at the time of ore deposition the approximate temperature of ore deposition—that is to say, in hot rocks. With a maximum temperature of ore deposition of, say, 575 degrees centigrade, as determined above, I have postulated a minimum temperature of 365 degrees centigrade, the critical temperature of water, since the whole range of ores appear to behave as if their mother solution or magma was in a condition of gaseous tension. Substantially these same limits of temperature must have obtained in the wall rock into which were injected the Cornwall veins which I have taken as an example. If such a mixed ore magma as is evidenced in Cornwall had been injected into a wall rock cooler at the outset than the critical temperature of the lead-silver zone, then all the metals would evidently have been thrown down at once and we should have had veins of a complex ore containing tin, tungsten, copper, zinc, lead, and silver. It also follows from all this that ore magmas are *sensitively affected* by the temperature of the wall rocks as they migrate along fissures, and are unable of themselves to long retain their heat. This is partly due, of course, to the narrow widths of the migrating fluid masses.

Passing now to the consideration of rock magmas, it seems clear that very narrow dikes must have much the same close dependence on the temperature of the wall rocks; that while rock magma may retain its heat somewhat better than ore magma, being less volatile and active, yet very narrow dikes can penetrate only wall rocks of a temperature a little lower than the freezing temperature of the dike itself. Persistent narrow dikes accordingly connote hot rocks at the time of their injection and, indeed, rocks whose temperature was nearly that of their freezing point. It would therefore appear that these very narrow dikes may have much the same significance in registering rock temperature as pegmatite and mineral veins and veindikes; and that if we may use, as it above appears, the metal zones as a geothermometer to measure the heat of the rocks at the time of their injection and consolidation, narrow dikes may also be part of the thermometric scale. Larger advancing masses of rock magma, of course, carry their own heat and heat the wall rocks in advance of their progress.

I have tried to demonstrate in my book, "Ore Magmas," that most metallic ores have in most cases been injected as magmas (containing various proportions of water and other gases), as a definite phase of a magmatic differentiation (magmation) series, the ore magmas having originated by differentiation in depth and having penetrated upward if a favorable opportunity presented. Ordinarily the ore injection is the last of the magmatic series, which spring at a given intrusion epoch from a given magmatic center; and the reason for this I have held to be largely that the ore magmas cooled or froze at a lower temperature than the rock magmas proper. I have called attention to the fact that in general the temperature of ore crystallization—such as a veindike crystallization—is evidently lower than that of the rock crystallization, so that the general rule is that where a vein of ore is closely associated with a dike (of rock), the vein typically follows the dike, although the reverse order obtains here and there.

Post-ore basic Dike Injections

GENERAL STATEMENT

It is now my purpose to pursue a certain phase of this subject further, and to examine into certain cases of the relation of ore injection to dike injection, namely, those cases where the ore injection is not the last of the magmatic invasions, but is followed or accompanied by dikes. Certain features concerning these post-ore dike injections attracted my attention as much as three or four years ago, but I felt that I should collect more data before drawing conclusions. I will now set forth certain data and later consider whether any new lessons may be drawn from them.

BASIC DIKES AND GOLD-QUARTZ VEINS

I shall first cite a number of cases from the deep-seated gold-quartz veins. At Silver Peak, in Nevada,[9] there are typical gold-quartz veins, consisting of coarse translucent quartz in lenses, with sparse sulphides and free gold. The main igneous event here was an intrusion of granite into Cambrian sediments, probably in post-Jurassic time, like the main intrusion in the Sierra Nevada. The granite was followed by alaskite intrusions, and these by the quartz veindikes. Later than the quartz veindikes came trap dikes (diorite), the largest of which cut the veindikes at right angles, running nearly north and south, whereas the veindikes run nearly east and west,[10] though they also run parallel to the veindikes and alongside of them or in them (figure 1).

[9] J. E. Spurr: Prof. Paper 55, U. S. Geol. Surv.
[10] Op. cit., plate viii.

As in nearly all gold-quartz veins, the richest ore was subsequent to the crystallization of the quartz, and consisted mainly of sparse (auriferous) sulphides which crystallized in cracks formed in the quartz,[11] and the relation of these cracks to the diorite dikes which run along the veins indicates that the cracks may have been formed by the dike intrusion. I believe, as a result of all my study of veins of this type, that the sulphides in the fractures of the quartz crystallized from the same ore magma as the quartz, but at a lower temperature, and therefore a little later. If this is so, the ore magma (principally quartz) and the diorite magma were practically contemporaneous injections.

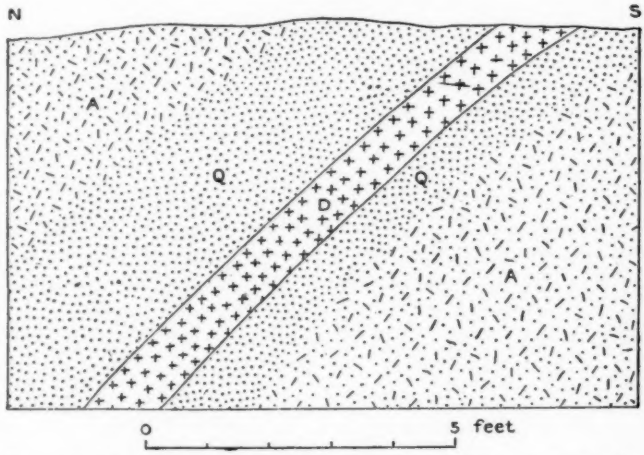

FIGURE 1.—*Vertical Section in Drift, Hickey Tunnel, Silver Peak, Nevada*

Showing intrusive diorite splitting earlier quartz lens. A, Coarse alaskite (country rock of quartz); Q, quartz; D, diorite. After J. E. Spurr, Professional Paper number 55, United States Geological Survey, page 44.

The gold-quartz veins of north central Idaho have the same relations to basic dikes as have those of Silver Peak. According to Dr. Francis A. Thomson,[12] the veins occur near a granite batholith and give evidence of derivation from the granite magma; "graditional phases going from pegmatite to vein quartz and back to pegmatite again in the same fissure are not uncommon." Basic (diabase) dikes are later than the quartz veins, are closely associated with them, and are apparently about the same age as the later stage of the quartz veins, which stage carried gold- and silver-

[11] Ore Magmas, p. 255.
[12] Eng. Min. Jour. Press, Oct. 4, 1924, p. 533.

bearing sulphides and penetrated along fissures in the earlier and more or less barren quartz veins (figure 2).

At the gold-mining camp of Porcupine, in Ontario, the ancient Keeweenawan lavas and sediments were intruded, still in pre-Cambrian time, by the following magmatic sequence: (1) quartz porphyries grading to syenite porphyries, in large masses; (2) quartz veindikes carrying gold; (3) occasional augite diabase dikes; (4) olivine diabase dikes. The porphyry has been intensively sheared with the rock which it has intruded, but the quartz veins and the post-mineral diabase dikes have not been sheared, although the quartz has been deformed a little.[13]

At Kirkland Lake, Ontario, where there are gold veins of the same general age as at Porcupine, there is a similar series: (1) Intrusions of

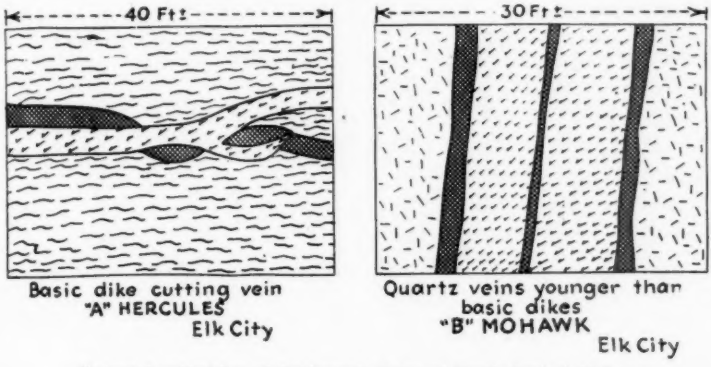

FIGURE 2.—*Sketches of Gold-quartz Veins of North Central Idaho*

Showing in one case a basic dike younger than the quartz vein; in another case the dike older than the vein. The quartz is shown by dark cross-hatching. After Francis A. Thomson, Engineering and Mining Journal-Press, October 4, 1924, page 538.

alkaline igneous rocks, such as syenite; (2) the injection of gold-bearing ore solutions; (3) dikes of olivine diabase transversal to the mineral veins.

Nevertheless, there is at Kirkland Lake, in the Teck-Hughes mine, some mineralization subsequent to one of the cross-cutting diabase dikes, which is faulted, the fault following the plane of the vein. Mr. D. L. H. Forbes, general superintendent of the mine, has made for me the accompanying sketch of the occurrence (figure 3).

It would appear, therefore, that while in general the diabase dikes are later than the ore, some of the ore is later than some of the dikes, which

[13] Summary by J. E. Spurr: Eng. and Min. Jour. Press, Oct. 13, 1923, p. 633.

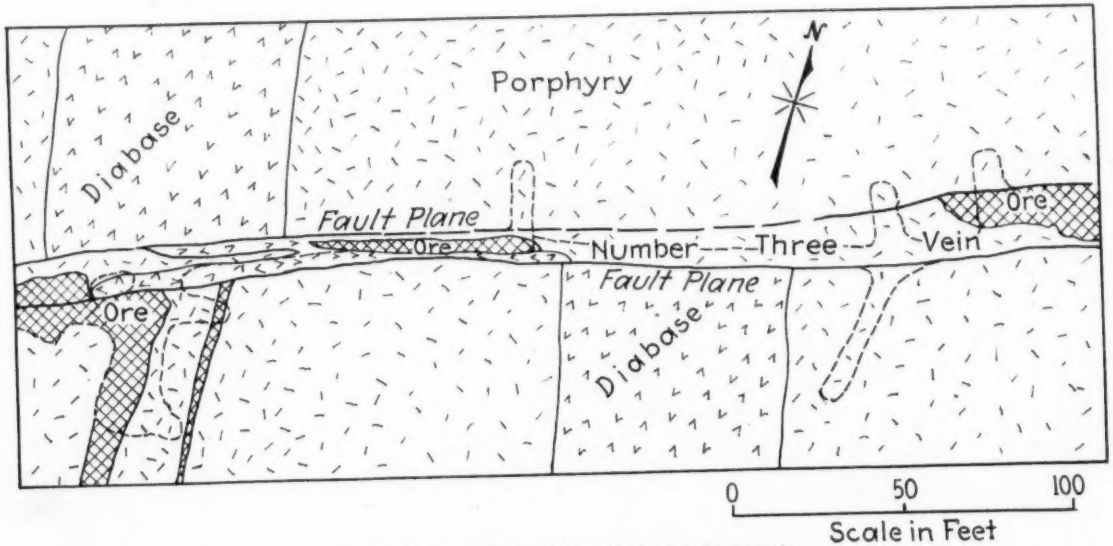

FIGURE 3.—*Teck-Hughes Mine, Kirkland Lake, Ontario*

Relation of diabase dike to Number Three Vein ore-bodies near dike.

would argue that the period of ore injection overlapped on that of diabase dike injection, and that to that extent the ore magmas and the dike magmas were contemporaneous—an identical condition which has been inferred for Silver Peak. The ores at Kirkland Lake are not veindikes, but I have held them[14] to represent the last crystallized phase of the typical gold-quartz magmas, and to correspond with the slightly later sulphide stage at Silver Peak.

At many other localities in Ontario and Quebec, as has been recorded in the publications of the Canadian Government geologists and elsewhere, gold-quartz veins are cut by later basic dikes. In Nova Scotia, where gold-quartz veins (veindikes) are associated with the intrusion of probably Devonian granite, in one locality (Tangier district)[15] a "dioritic dike" cuts the strata and parallel quartz veins at right angles. It is not auriferous.

H. W. Turner[16] has described the Wilshire gold mine in Inyo County, California, which is a vein lying in a quartzite reef situated between masses of granite rock. The quartzite is considered by Knopf[17] as a "roof-pendant" in the batholith of granite, which presumably is post-Jurassic, like the rest of the Sierra Nevada batholiths. Besides the gold, the ore carries pyrrhotite, with some arsenopyrite, sphalerite, chalcopyrite, pyrite, and molybdenite.

Turner writes:

> "The Wilshire reef is intersected in places by granite dikes, and these contain some pyrite, suggesting that they were intruded before the period of mineralization. In addition, on the first level west there are narrow, dark, basaltic-looking dikes that do not appear to be mineralized, and hence were intruded after the period of mineralization. Knopf has identified this dark dike rock as lamprophyre."

Concerning the gold-quartz veins of Victoria, in Australia, and their relation to basic dikes, I have summarized the situation in "The Ore Magmas"[18] as follows: . . . "the gold veins of Victoria, Australia, are associated with large intrusions of granodiorite or quartz monzonite, with dikes of quartz-feldspar porphyries (alaskites), of diorite and gabbro, and narrow hornblende and biotite dikes (lamprophyres) and basalt porphyry. The relative bulk of the different intrusions, as described, however, as well as the mineral composition—biotite, feldspar, and

[14] Eng. and Min. Jour., vol. 116, p. 671.
[15] W. Malcolm: Gold fields of Nova Scotia, p. 239, Memoir No. 20-E, Canada Dept. of Mines, 1912.
[16] Eng. and Min. Jour. Press, vol. 114, no. 21, Nov. 18, 1922, p. 889.
[17] Bull. 640-I, U. S. Geol. Surv., p. 236.
[18] Vol. ii, p. 594.

quartz, with some hornblende—which runs through all, indicates a differentiated intermediate-siliceous magma (granodiorite to quartz monzonite). The veins are of quartz, of the type which I denominate as intrusive, and carry less than 2 per cent of sulphide minerals and gold. The quartz veins are most commonly 'related to lamprophyre and diorite porphyry dikes, but some are associated with granodiorite intrusions and quartz porphyry dikes and rarely with rocks of basaltic composition.' (The quoted matter immediately above is from M. R. Junner's article: Gold Occurrences of Victoria, Australia, published in Economic Geology, vol. xvi, number 2, March, 1921, on p. 83.)

"This frequent association with basic dikes, can not, however, lead us astray for a minute; for the type of veins is a typical siliceous end-product from an intermediate-siliceous magma (quartz monzonite); and its juxtaposition with basic dikes is plainly fortuitous, unless at times there may be some coupling on account of vein and dike being complementary—siliceous and basic extremes of differentiation."

The number of cases of gold-quartz veins closely associated with diabase (frequently later) are so numerous that it would be tedious to enumerate them further.

BASIC DIKES AND NICKEL-COPPER ORES

Let us next consider the magmatic succession in a nickel-copper region: At the nickel mines at Sudbury, in Ontario, a typical magmatic succession was: (1) diorite (which separated into a norite below and a granite-syenite above); (2) granite dikes; (3) ore veindikes[19] (pyrrhotite, chalcopyrite, pentlandite); (4) trap (diabase) dikes; (5) olivine diabase dikes. All of these magmatic phases are evidently closely related. None of the rocks of this sequence have undergone shearing.

The above is the succession at the Creighton mines, as given by C. W. Knight. The geological succession at the Worthington mine, as given by Knight, is of great interest.[20] Quartzites and conglomerates of the Temiskaming (pre-Cambrian) series were tilted nearly vertical and were intruded by greenstone. Then came a norite dike. This was brecciated, after solidification, for a width of 50 or 60 feet, and the ore sulphides were introduced.

"When the period of mineralization ceased, or about ceased, the norite dike and sedimentary rocks were fissured in two places and dikes of trap were introduced." Subsequently, came several dikes of diabase, and after

[19] The terms veindikes here is my own, not Knight's.
[20] Report of the Ontario Nickel Commission, 1917, p. 174.

this veins one to six inches wide "containing calcite, galena, zinc blende, and iron pyrites."

This last ore deposition evidently represents a cooler metal zone (the zinc-lead zone) normally overlying the nickel-copper zone of the main and earlier mineralization.[21] The formation of the zinc-lead zone denotes a dropping of the isogeotherms during the critical period of ore injection.[22]

It will be noted that basic dike rocks were intruded between the periods of the copper-nickel and of the zinc-lead ore-magma injections, and hence that in a general way the basic rock magmas and the ore magmas were contemporaneous. Knight reports, even, that a slight residual portion of the copper-nickel ore deposition took place after the injection of the trap dikes, the ore being found along the margins of some of the dikes. This is an analogous relation to that which exists between the gold ores and the trap (diorite) dikes at Silver Peak. At Sudbury the apparent indication would be that the trap magmas had a freezing temperature between that of the nickel-copper magma and the zinc-lead magma.

Passing upward in the zonal column of ores, I will cite some copper camps. The Rossland district, in British Columbia, contains fissure veins in intrusive monzonite and augite porphyrite. Granodiorite occurs in the vicinity, representing probably portions of a great batholith of immediately post-Jurassic age, like the main intrusive batholiths of the Sierra Nevada. The ores are believed to be closely related to the batholithic intrusions. Lindgren says:[23] "The veins were formed within the epoch of intrusion, for they are intersected by many basic dikes related to camptonite." These later lamprophyric dikes are believed by Drysdale to belong to a distinctly later igneous period than the ore and the premineral intrusions;[24] but he also writes that "some of the lamprophyres are older than the main fissures and are found both cut off by the veins and as inclusions in the ore."[25] Since these pre-vein lamprophyres (in part at least) correspond in strike (north to south) with the post-vein lamprophyres, cutting the veins nearly at right angles, I am inclined toward Lindgren's interpretation.

One of the figures shown by Drysdale (figure 11, p. 55) is labeled "Vein cutting dike, but constricted by it" (figure 4), but is hardly intelligible as thus interpreted. The more apparent explanation for the

[21] The Ore Magmas, vol. ii, p. 588.
[22] J. E. Spurr: Economic Geology, vol. ii, no. 8, Dec., 1907, p. 792.
[23] "Mineral deposits," McGraw-Hill, 2d edition, p. 698.
[24] C. W. Drysdale: Memoir 64, Canada Geological Survey, 1915, pp. 55, 243.
[25] Op. cit., pp. 53, 54.

figure is that the vein was intruded by the later cross-cutting lamprophyre dike; that thereafter the vein was reopened by a renewal of the fissuring along one wall, and, the new opening being filled by vein material, the whole vein was thus widened. This explanation would make this vein in the large sense *contemporaneous* with the dike—an interpretation which would link up the pre-vein and the post-vein lamprophyres as belonging to the same general period of intrusion. The ores are of gold, copper, and silver; the metallic minerals are chalcopyrite and pyrrhotite, with some pyrite, magnetite, arsenopyrite, molybdenite, and bismuthinite. The gangue minerals are quartz, calcite, and biotite, with some garnet, actinolite, and wollastonite.

At Jerome, in Arizona, in the United Verde mine, according to Reber,[26] pre-Cambrian greenstones and later sedimentaries were invaded

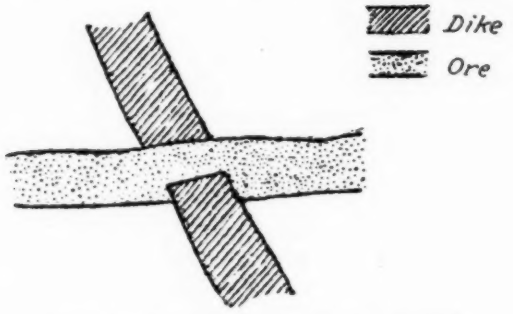

FIGURE 4.—*Reproduction of Figure 11 of Drysdale*
Memoir 64, Canadian Geological Survey, 1915, page 55. (See text.)

by (1) masses of quartz porphyry, which was later rendered schistose. Later came (2) intrusive masses of augite diorite, and (3) subsequently the great masses of copper ores (quartz, pyrite, and chalcopyrite) were formed. "After the formation of the large schist replacement ore bodies, *but before the mineralization was entirely completed,*[27] a series of small diorite or andesite dikes cut the ore masses and the earlier rocks." All these igneous rocks seem to represent a general magmatic period, and all are held to be genetically related to an immense granite batholith whose outcrops approach Jerome. *Here, then, we have ore preceded by siliceous and basic rock magma injections, and succeeded by and even partly contemporaneous with basic rock-magma injections.*

[26] Trans. Am. Inst. Min. Eng., vol. xvi, p. 6.
[27] The italics are mine. J. E. S.

BASIC DIKES AND LEAD-ZINC ORES

The Ainsworth district, in British Columbia, lies on the shore of Kootenay Lake.[28] The ores are galena-blende-pyrite ores, carrying silver, and occur as replacement deposits and as true fissure veins. Basic (lamprophyric) dikes occur near the veins. Camptonite containing crystals of hornblende and some of biotite is the common type. In some places the lamprophyre is older than the ore; in other places younger. Schofield states:[29] "It can at least be concluded that *the dikes and ore deposits are nearly contemporaneous in age,*[30] and that the dikes have no genetic connection with the ore deposition." The ores are believed to have emanated from the West Kootenay granite batholith, which is of Jurassic age.

As an example of post-ore intrusions in a zinc-lead district, Mr. Walter Harvey Weed furnishes me the following notes concerning post-ore diabase at Wallace, Idaho:

"Diabase and lamprophyre dikes of slightly more recent age than the ores can be seen at the Hecla, Hercules, Interstate, and other big mines near Wallace, Idaho. At the Interstate mine such dikes may be seen on several levels and also in the mine stopes. The Interstate mine is in Pritchard slate, the oldest formation of the Cœur d'Alene pre-Cambrian series, which in this vicinity is cut by an intrusive mass of monzonite (and by dikes of monzonite porphyry), with which the ore deposits are genetically connected. At the Interstate the monzonite is bordered by aplite, pegmatite, and magmatic quartz; this quartz also forms veins, one of which, the Laura, contains much tetrahedrite and galena, but not in commercial amount.

"The Interstate vein is later, truncating quartz veins in several places. . . . The ore consists of sphalerite with a lesser amount of galena, in practically unaltered slate; quartz and rarely siderite form a very small part of the ore. . . . The galena is later than the sphalerite and is noticeably more abundant at the ends of the ore shoot. The vein crosses a dike of monzonite porphyry at a very slight angle and without displacement, and both ore and porphyry are cut by the diabase dikes, which have a prevailing north to south direction (roughly at right angles to the vein) and a steep dip. Diabase dikes as well as ore and porphyry are cut and displaced by a strike fault cutting the porphyry at a small angle, but with a displacement of 110 feet to 150 feet. In the Hecla mine a contact chilling or skin has been observed on a basic dike that follows the ore, but such contact phenomena have not been seen in the Interstate."

The condition recorded in the last sentence might be interpreted as indicating that in the Interstate the basic dike was intruded into ore and

[28] S. J. Schofield: Mem. 117, Canada Geol. Survey, 1920.
[29] Op. cit., p. 36.
[30] Italics are mine. J. E. S.

rock which was only very slightly cooler than the temperature of dike freezing, whereas in the Hecla the ore and rock was relatively somewhat cooler; and this would imply that the rocks were hot when the dikes came in.

Concerning further the association of lamprophyre dikes with silver ores in Idaho, Dr. Edward Sampson, of the U. S. Geological Survey, supplies me with the following notes covering work in which Mr. J. L. Gillson was associated with him:

"In the Pend d'Oreille district, Idaho, about 40 miles north of the Cœur d'Alene district, lamprophyres are associated with silver ores.

"The sequence of events is this: (1) Formation of zones of intense shearing—up to 100 feet or so; (2) Formation of quartz veins, perhaps by injection; some quartz masses are very heavy. Local intense silicification of country rock. Some sulphides were contemporaneous with quartz, some later. The principal sulphides are galena, sphalerite, tetrahedrite, pyrite, arsenopyrite, and stibnite; (3) Intrusion of lamprophyre dikes, cutting quartz veins—probably most abundant where there is most ore; (4) Local intense hydrothermal alteration of dikes; (5) Renewal of shearing, local but not common."

I have described the important lead-silver camp of Mapimi, in Mexico, in "The Ore Magmas."[31] Mesozoic limestones and shales have been intruded by two types of igneous rock—first, alaskite, and later diorite, both in large bodies. The ore deposition (zinc, lead, and silver mainly) took place at a period between the two periods of igneous intrusion—later than the alaskite and earlier than the diorite. Both alaskite and diorite are evidently due to differentiation from a common underlying magmatic reservoir of monzonitic composition, and the ores are held to have resulted from the injection of an ore magma derived from the same general magmatic source.

It is easy to find instances which form exceptions to what I believe to be the rule, as above indicated, but their recording and discussion should be left to a later time.

TENTATIVE CONCLUSIONS

From the above cases, and from numerous others which have come to my attention, I suspect that we may draw certain tentative conclusions:

1. Basic dikes, "trap" or "lamprophyre," occur in connection with many ore deposits.

2. In many observed cases these dikes are later than gold-quartz veins, which themselves are later than granite or other major intrusions. They

[31] Vol. I, pp. 201-203.

are also in many cases later than ores carrying nickel, or copper, or even zinc and lead.

3. In repeated cases, however, these basic dikes were contemporaneous with the final (sulphide) phase of consolidation of the gold-quartz magma (Silver Peak, Kirkland Lake); and elsewhere (Sudbury, Jerome, Rossland) were contemporaneous with the final phase of the copper-magma injection, but earlier than the zinc-lead magma injection where this occurs (as at Sudbury).

4. These repeated instances lead to the working hypothesis that the temperature of consolidation of these basic dikes corresponded with the temperature of consolidation of the ore magmas, being less than that of the granites and the quartz consolidation of the gold-quartz magma and seeming to correspond roughly with the temperature of the copper zone, or even sometimes of the zinc-lead sequence of the typical ore magma succession—a sequence marked by falling temperature.[32]

5. The fact that faulting usually has set in after the intrusion of these trap dikes, together with the mentioned fact that the dikes, like the veins, have followed fissures of little or no displacement, would indicate of itself their close contemporaneity, both antedating the long period of faulting and adjustment which seems to result from long cooling, especially in the case of intrusions near the surface. Thus, in the case cited by Mr. Weed at Wallace, faulting followed both the ore and the trap dike; and in the case described by Dr. Sampson hydrothermal alteration, so often characteristic of the wall rock of ore bodies (and usually, therefore, interpreted as "accompanying" the ores), occurred after the intrusion of the dikes which followed the ores!

BASIC DIKES AND SHALLOW ORES

The above cited cases are of ore deposits and rocks injected at considerable to great depths. The following cases refer to magmatic sequences at Tertiary volcanic craters and took place quite near the original surface, according to the universal opinion of geologists.

Cripple Creek and Silver Cliff, both in Colorado, show ore injection as a stage of igneous injection. These are ores connected with Tertiary volcanoes—ores crystallized very near the surface. The Cripple Creek volcanoes, according to Lindgren and Ransome,[33] emitted successively (1) latite porphyry with syenite; (2) phonolite; (3) basaltic dike rocks (trachydolerite, vogesite, and porphyritic olivine basalt—limburgite or

[32] The Ore Magmas, vol. 1, p. 262.
[33] Prof. Paper 54, U. S. Geol. Surv., 1906.

monchiquite; (4) the ore deposits, which constituted the latest magmatic phase.[34] The ores are gold telluride, with pyrite, blende and galena, some stibnite and argentiferous tetrahedrite, molybdenite, and hübnerite, and rarely chalcopyrite. The chief gangue minerals are quartz, fluorite, and dolomite, with celestite, orthoclase, roscoelite, chalcedony, opal, rhodochrosite, calcite, and barite. The succession of minerals is not clearly marked, but in general is: *a*, molybdenite, blende, galena, pyrite, orthoclase (adularia); *b*, quartz, fluorite, and dolomite; *c*, gold tellurides and celestite; *d*, quartz and chalcedony.[35]

At Silver Cliff, in the Rosita mine, as at Cripple Creek, Tertiary lavas have broken up through pre-Cambrian granite and gneiss.[36] As at Cripple Creek, different lavas were erupted one after the other, indicating differentiation of an underlying magma, which was in a way similar to the Cripple Creek magma, both being unusually alkaline. The order was: (1) andesite, (2) dacite (quartz-andesite), (3) rhyolite, (4) andesite, (5) trachyte, (6) ore injection, (7) basaltic dike (limburgite).

The ores at Silver Cliff are zinc-lead-silver ores, with silver mostly associated with the galena. The sequence of deposition, as shown in successive coatings on the boulders (for the ore chimney is an agglomerate neck, probably produced by a gas explosion),[37] is: (1) blende-galena; (2) galena; (3) barren carbonates: *a*, dolomite; *b*, ankerite or siderite; *c*, calcite; (4) chalcedony.

Concerning this series I have observed:[38]

"Note that the lava succession in both Cripple Creek and Silver Cliff was closed by dikes of basalt porphyry ('limburgite' and 'monchiquite'), but that the ore deposition at Cripple Creek succeeded this basalt and at Silver Cliff immediately preceded it."

At the Braden mine, in Chile, as described by Lindgren and Bastin,[39] there was a magmatic sequence which I sum up as follows: (1) eruption of Tertiary surface volcanics; (2) intrusion of andesite porphyry; (3) alteration of andesite porphyry to sericite, quartz, tourmaline, and pyrite, with subordinate veins of quartz, tourmaline, pyrite, and chalcopyrite; (4) gas explosion and formation of a volcanic vent; (5) occupation of top of vent by a lake and deposition therein of tuff; (6) main ore deposition of quartz, tourmaline, biotite, pyrite, and chalcopyrite; (7) intrusion of

[34] J. E. Spurr: The Ore Magmas, vol. ii, p. 548.
[35] Prof. Paper 54, p. 176.
[36] S. F. Emmons: 17th Ann. Rep., U. S. Geol. Surv., Pt. 2, 1896, pp. 269-472.
[37] The Ore Magmas, vol. ii, p. 555.
[38] The Ore Magmas, vol. ii, p. 555.
[39] Economic Geology, vol. xvii, no. 2, March-April, 1922.

alkali dacite and latite porphyries and breccias; (8) rising of boron solutions and formation of tourmaline; (9) intrusion of granite porphyry breccia; (10) third period of surgence of copper-bearing solutions—deposition of chalcopyrite, pyrite, bornite, tennantite, siderite, rhodochrosite, and quartz; (11) intrusion of a lamprophyre dike.

If we eliminate for the moment the independent stages of non-metalliferous magmatic solutions, so as perhaps to admit of clearer comparison with the Colorado examples, we have as chief magmatic events: A, Tertiary surface volcanics; B, andesite porphyry intrusion; C, ore injection (repeated twice, with a considerable time interval); D, dacite and latite (and granite) porphyry intrusion; E, ore injection; F, lamprophyre dike. In all three cases (Cripple Creek, Silver Cliff, and Braden) there was, also, previous to the ore injection, a gas explosion, producing a pipe of volcanic agglomerate.

These three cases present, it would appear, too many points of similarity to be accidental. Considering, first, the relations of the ultimate basic dikes at Cripple Creek and the Rosita Hills to the ore injection, we note that the dikes are in part of identical nature—limburgite—in the two districts. The stages and sequence of ore at the Rosita Hills indicates mainly the lead-silver zone of temperature, with an initial temperature of the zinc-lead zone and a final barren gangue stage, indicating a lowering of temperature. Moreover, the stages of the earthy mineral deposition also indicate a lowering temperature.[40]

At Cripple Creek the mineral succession indicates a somewhat higher initial temperature of ore deposition and also a drop in temperature during crystallization, leading to the barren gangue stages, followed by the gold tellurides, which may indicate a somewhat higher temperature.[41] At any rate, the basic dikes, which were in each case the last lava injection, were essentially contemporaneous with the ore injection in each case, which would seem to indicate the possibility that the temperature of ore consolidation and dike consolidation was about the same; that, to try to fix our ideas a little more clearly, the temperature of dike consolidation was around the galena-blende stage.

And at the Braden mine we have the same evidence of rapid differentiation in the magma at the base of the volcano as in the case of the Cripple Creek and Rosita vents. As at these Colorado localities, the Braden volcano starts with an intermediate magma, followed by injections showing increasing silica and alkali content, with finally an ore

[40] The Ore Magmas, vol. ii, p. 804.
[41] The Ore Magmas, vol. ii, pp. 699-704.

magma and a basic dike. Here again the basic dike and the ore are coupled together. But there are further significant things in the Braden data. Both of the periods of ore (C and E in the above table) show, by their mineral contents, temperature sustained at that of the copper zone. Moreover, the C stage, above, consists of two periods, (3) and (6) in the first tabulation above, which both represent the copper zone, although there was a distinct time interval between; and this again suggests a relatively sustained equable temperature during the magmatic period. Nevertheless, the mineral combination of E does represent a slightly lower temperature than that of C, as may be seen by comparing it with the sequence at Matehuala, in Mexico (this conclusion being based on the relatively richer ores of copper which constitute E); and this is also the conclusion of Lindgren and Bastin, based on the less content of tourmaline in the E stage.[42] Here, then, we have dacite and latite porphyries intruded at the temperature of the copper zone, which I have roughly conjectured above at around 500 degrees centigrade;[43] and lamprophyre intruded at a little lower temperature. In the case of the dacite-latite intrusions, we appear at first glance to have a new element injected into our problem and one not concordant with the line of reasoning which we have been following, but on closer consideration the discordance disappears; for as regards these intrusions Lindgren and Bastin observe:[44]

"For the most part, these magmas solidified completely before they reached their present position, but continued their upward progress under the pressure of still molten magma below, becoming intimately brecciated by internal and external friction during the later part of their ascent."

The dacite-latite magma, then, largely *solidified* at a greater depth and a higher temperature than that of the copper zone; therefore its temperature of freezing was higher than that of the copper ore magmas. Examining the evidence of the granite porphyry intrusion (stage (9) in the first table above), the same conclusion appears. The granite porphyry is younger than the dacite and latite porphyries, being separated by a distinct time interval,[45] but antedates the last period of ore deposition (E, above), and is, "with the exception of the single dike of lamprophyre, the youngest formation of the crater." Concerning this granite porphyry our authors write:

"It crystallized at greater depths than those at which it is now found, and during or immediately after crystallization was forced upward into its present

[42] The Ore Magmas, vol. I, p. 258.
[43] The Ore Magmas, vol. I, p. 264.
[44] Economic Geology, vol. xvii, no. 2, p. 87.
[45] Lindgren and Bastin: Op. cit., p. 92.

position by the pressure of still molten or partly molten granite material below, becoming brecciated by friction, internal and external, during its upward progress."

Therefore the freezing temperature of the granite porphyry was higher than that of the copper ores; and, indeed, we may surmise somewhat higher than that of the dacite and latite porphyries, which, unlike the granite porphyry, retained some still fluid portions at this horizon. But the lamprophyre not only intruded this horizon, but consolidated at it; hence its freezing temperature is indicated at a little lower than the copper zone, or perhaps about the same.

Temperature of basic Dikes

Certainly the observations which I have cited in this paper hitherto are all too fragmentary to be finally conclusive; but if I should multiply them further (as I could easily do) they would become tedious. Summarizing the consideration of instances of relatively deep-seated or "plutonic" magma sequences involving ore injection leads to the hypothesis that basic dikes were injected at a temperature corresponding with the copper zone, or even sometimes with the zinc-lead zone, of the typical ore-magma succession; and by consideration of three cases of superficial volcanic sequences involving ore injection we arrive at precisely the same conclusion. Moreover, in all these cases the attendant conclusion is present (which is clinched by a special type of argument at the Braden mine), that the siliceous and intermediate intrusions have consolidated at a higher temperature than that of the whole ore sequence, and the general indication is that the consolidation temperature of the magmas involved became lower as they became femic.

The temperature of the copper-zinc-lead zones I have estimated at around 400 to 500 degrees centigrade, based on various clues,[46] and accordingly these ultimate basic dikes would be held to have consolidated at this temperature. Granites, however, have been held to crystallize above 575 degrees centigrade[47]—a conclusion based on the inversion point of quartz—and experimental data as to the formation of hornblende, mica, and orthoclase is in accord,[48] all tending to suggest a temperature of crystallization of granites and granite porphyries not much over 575 degrees or, let us assume, 600 to 700 degrees.

[46] The Ore Magmas, pp. 79, 516, 567, 637, 657.
[47] Wright and Larsen: American Journal of Science, 1909, vol. xxvii, p. 447.
[48] The Ore Magmas, vol. i, p. 303.

Based on these data, we have the following temperature scale for consolidation or freezing below the surface:

Freezing Temperatures in Depth

	Rock magmas	Pegmatore magmas
700 degrees centigrade		
600 degrees centigrade	Granites and Rhyolites	
	Diorites and Andesites	Granitic pegmatites (and aplites)
	Diabases	Tin, Gold-quartz,
500 degrees centigrade	and	Tungsten, Nickel
	Basalts	Copper
	Ultrabasic	Zinc
400 degrees centigrade	rocks	Lead
		Silver

Nature of cited basic Dikes

In many of the cases above mentioned the ultimate basic dikes have been referred to as "lamprophyres" by those who have described them. Such, for example, are the case in Inyo County, California (page 553); at Rossland, in British Columbia (page 555); at Wallace, Idaho (page 557), and at the Braden mine (page 561). What is a lamprophyre? It is a group name and not in universal use. I do not find it listed in the index to Daly's "Igneous Rocks." Kemp's "Handbook of Rocks" defines lamprophyres as "dike rocks of porphyritic texture, whose predominant phenocrysts are the dark silicates, augite, hornblende, or biotite. They are practically basic dikes."

Niggli[49] observes:

"Almost as constant accompaniments of granite as the aplites are the lamprophyres, which are silica-poor products of differentiation. Their intrusion generally follows that of the aplites. . . . Doubtless the mineralizers, especially H_2O, play a rôle in the differentiation of the special magma. This is shown by the usually high biotite or hornblende content. . . . Aplite and lamprophyre show a complementary relation when compared with the main intrusion."

The lamprophyres described by Niggli contain augite, hornblende, and mica in various proportions, with soda-lime feldspars. They include

[49] Die Leichtflüchtigen Bestandtheile im Magma. Leipzig, 1920, p. 129.

various types to which special names have been given: camptonite, kersantite, odinite, luciite, cuselite, theralite-diabase. None of them are described as containing olivine; otherwise, as Kemp observes, they are essentially basic dikes—"trap" dikes.

The above observations by Niggli, that the lamprophyres are later than the aplites, corresponds with the above recorded relations of the lamprophyres with the ore injections, since the latter are subsequent to the pegmatites, which are in general contemporaneous with the aplites. But there are some of the basic dikes in the cases I have recorded, like some of those at Porcupine, Sudbury, and elsewhere, which contain olivine and become olivine-diabase or basalt.

The Silver Peak basic dikes are plagioclase-hornblende rocks—diorites—containing quartz in places, making a quartz-diorite phase. The feldspar is andesine and labradorite. Some phases are largely of hornblende.[50] Evidently this may be placed in the "lamprophyre" group. The analysis is given below. The basic dikes of the Porcupine region have been described as diabase and olivine diabase. They contain plagioclase and augite and some olivine.[51] Other occurrences of basic dikes in connection with gold-quartz veins in Ontario, however, are classed as diorites.[52] The basic dikes of Victoria, Australia, are "diorite and gabbro porphyries," and contain chiefly plagioclase (andesine and labradorite) and hornblende, with some quartz, biotite, and augite.[53] These rocks are closely connected with the gold veins, but earlier, so far as described.

At Sudbury, at the Worthington mine (a key occurrence, as above described), the (earlier) trap dikes are described as having the composition given in the table below.[54] The subsequent olivine diabase dikes have the analysis which follows that given for the trap. Both these dikes were intruded midway in the general ore-injection period. At the Creighton mine, where "trap" dikes also precede olivine diabase dikes, the analysis of the trap is as below.[55] This trap-diabase sequence is repeated elsewhere in the district.[56] The traps are said to have the "composition of uralitic diabase."[57]

In the Rossland district the lamprophyric dikes vary in composition.

[50] J. E. Spurr: Prof. Paper 55, U. S. Geol. Surv., p. 26.
[51] A. G. Burrows: 20th Annual Report, Ontario Bureau of Mines, vol. xx, pt. ii, p. 17.
[52] Percy E. Hopkins: Ont. Dept. of Mines, vol. xxx, pt. ii, 1921, p. 18.
[53] N. E. Junner: Econ. Geol., March, 1921, vol. xvi, no. 2, p. 85.
[54] Royal Ontario Nickel Commission, 1917, p. 178.
[55] Op. cit., p. 150.
[56] Op. cit., p. 134.
[57] Op. cit., p. 109.

The dike (figure 4) which I believe to be contemporaneous with the vein is described as a "mica-lamprophyre."[58] The basic dikes near Wallace, Idaho, consist, according to Mr. Weed, of "diabase and lamprophyre" (page 557). The post-ore basic intrusion at Mapimi, in Mexico, is a diorite (page 558). The basaltic dike rocks of Cripple Creek consist of trachydolerite (principally plagioclase, pyroxene, and olivine), vogesite (principally orthoclase, hornblende, pyroxene, and biotite), and monchiquite (pyroxene, olivine, and andesine). Analyses of these rocks are given in the accompanying table. At Silver Cliff the basic dike, which is later than the mineralization, is limburgite, consisting essentially of olivine, augite, and magnetite.[59]

Dikes Contemporaneous with Ore Period

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Silver Peak diorite[60]	48.67	....	....	....	8.75	8.58	3.39	.99
Silver Peak diorite[60]	46.28	....	....	....	19.54	9.91	2.21	1.89
Sudbury trap[61]	52.54	16.10	5.88	9.94	1.66	7.35	3.02	1.58
Sudbury trap[62]	55.37	15.30	....	12.99	4.35	7.75	....	....
Sudbury olivine diabase[63]	49.05	16.96	....	14.91	5.27	7.75	....	....
Cripple Creek trachydolerite[64]	48.76	17.04	5.04	3.47	4.57	8.64	4.27	3.39
Cripple Creek vogesite[64]	47.31	16.21	5.05	2.90	3.08	7.11	3.92	3.73
Cripple Creek monchiquite[64]	44.08	12.80	4.58	3.72	7.22	11.21	2.97	3.31

It is a pity that we do not have more analyses, and that what we do have are so incomplete. In the last two analyses from Sudbury it is to be assumed that all the iron is given as FeO. Nevertheless, if we eliminate the second Silver Peak analysis, which is a special phase of the diorite, consisting chiefly of hornblende, and if we also except for the moment the monchiquite of Cripple Creek, we have a group which falls within a fairly narrow range of silica content—from 47 to 55—corresponding in general with the basalt-diabase-gabbro analysis, while the monchiquite of Cripple Creek, of course, is considerably less salic, falling in that respect into the class of least siliceous magmas. The sequence between earlier "trap" (silica, 52 to 55 per cent) and later olivine diabase

[58] Drysdale: Op. cit., p. 54.
[59] C. W. Cross: 17th Ann. Report, U. S. Geol. Surv., pt. II, p. 313.
[60] Prof. Paper 55, U. S. Geol. Surv., p. 26.
[61] Report Ont. Nickel Com., p. 150, Creighton mine.
[62] Op. cit., p. 178.
[63] Loc. cit.
[64] Prof. Paper 54, U. S. Geol. Surv., p. 93.

(silica, 49 per cent), which seems to occur repeatedly at Sudbury, might indicate the same tentative conclusion reached on page 555, that the latter consolidated at a somewhat lower temperature than the former, especially in view of the evidence, presented at the Worthington mine, of a falling temperature during this period of dike intrusion, as indicated by the sequence of metal injections.

Mineralogically, also, the dikes of this type range from diorites to diabases, and to special mineralogical types; so that if we conclude that their temperature of consolidation was 400 to 500 degrees centigrade, as above, we are, it seems to me, bound to suspect that the basic or basaltic magmas in general consolidate at that temperature in depth. We have, therefore, apparently not only to do with a special phase of basic dike rock called "lamprophyres," but with the basic magmas in general, since many of the dikes in question are typical diorites or diabases or olivine-diabases and occur under the same circumstances as those rarer ones which are rich in hornblende and mica, which have been called lamprophyres. The frequent presence of these lamprophyres in the ultimate basic dike group is probably illuminating, especially if we accept Niggli's suggestion, given above, that the gases, especially water gas, have an important part in the differentiation.

Lowering of Magma Temperature by Gases

General statement

We can then understand that these basic magmas may have remained fluid at the relatively low temperature indicated, largely on account of the gaseous magmatic elements present; and it would appear that this consideration extends not only to the lamprophyre magmas, but to basic magmas in general. We have reconciled ourselves to the view that granitic magmas remain fluid at temperatures around 600 to 700 degrees centigrade, by virtue of the gaseous constituents; but we have been prone to assume tacitly, or without much thought, that the more basic magmas represented more nearly the conditions of a dry melt. The data which we are considering, however, would suggest that the gaseous magmatic elements are as integral a part of the magma in the basic phases as in the siliceous ores, even if not present in nearly so large a proportion; and that if the refractory salic magmas are brought down to a low freezing temperature by these gaseous components, the far less refractory femic magmas have been brought down to a still lower freezing point by the same agency.

At the volcano of Kilauea, in the Hawaiian Islands, Day and Shepherd[65] have made valuable observations. The lava, which is active and fluid, is a basalt (SiO 49-50 per cent), with a surface temperature of about 1,000 degrees to 1,200 degrees centigrade.[66] They found the gases which escape everywhere from the lava surface to consist of water, carbon dioxide and monoxide, hydrogen, nitrogen, sulphur dioxide, and free sulphur, with a little chlorine and fluorine. Concerning the interreactions among these gases, the authors write:[67]

"The second consequence of the gradual release of gases is the interreaction between the gases thus set free in constantly increasing quantity as the surface is approached. These reactions are accompanied by evolution of heat, which obviously operates to raise the temperature of the surrounding lava so long as the reacting gases remain in contact with it. The heat generated by these gas reactions in the region near the surface where the amount is large may well be much more than sufficient to counteract the cooling effect of the expansion within the rising lava column, which may thus become hotter and not cooler as it approaches the surface."

The authors also consider all the gases released at the surface as magmatic:

"To us, therefore, such evidence as there is appears to indicate that the water released from the liquid lava when it reaches the surface is entitled to be considered an original component of the lava with as much right as the sulphur or the carbon."[68]

BASIC MAGMA TEMPERATURE IN DEPTH

If it is true that the surface temperature of congealing basic lavas (and, indeed, siliceous lavas) is about twice the freezing temperature of the same magmas in depth, how deep does the surface heat go? Day and Shepherd, as above noted, connect the surface heating with the release of gases from the magma when near the surface. Possibly the study of ore deposits may afford a useful clue here also. I have pointed out that the "dumping horizon," as I may call it, of the ore magmas is not at the surface, but at a horizon a few hundred feet below the surface, which I have placed as probably not more than 500 to 1,000 feet; and I have argued that at the horizon in question the gravity pressure is no longer sufficient to overcome the gaseous tension of the volatile components of the ore magma, which thereupon escape; so that the ore magma disintegrates

[65] Smithsonian Report for 1913, pp. 275-305.
[66] Op. cit., p. 279.
[67] Op. cit., p. 299.
[68] Op. cit., p. 305.

(regardless of temperature) and the solid portion is thrown down.[69] I see no reason why at this same horizon, or somewhat lower, the gases do not begin to escape from the lavas, although, on account of the relatively minor rôle which the gases play in the rock magmas and their less free play in them, the lava (unlike the pegmatites and ores) nevertheless reaches the surface, although exuding gases all along the route and after reaching the top. On this reasoning, the normal lower magmatic temperatures may obtain from this critical horizon of, say, 500 to 1,000 feet in depth downward, while the temperature rises continually from this horizon to the surface.

How deep, then, do these assumed moderate normal freezing temperatures go, of, say, 400 to 500 degrees for basaltic magmas and 600 to 700 degrees for the granitic magmas? Pegmatites, which are generally held to have frozen below 575 degrees centigrade, are especially characteristic of the greatest depths revealed by erosion; therefore they indicate wall rocks as cool or cooler than this temperature. The various metal zones of ore deposition have taken place at greatly differing depths, and even in the deepest zones—those of tin, tungsten, and the gold-quartz veins, for example—the crystallization or freezing temperature is indicated as below 575 degrees.

This conclusion I have held to apply to the deep gold deposits of Canada and California, as well as to the superficial deposits of Cripple Creek in Colorado, and the Braden in Chile. The Tertiary deposits were formed within a distance from the surface easily measured in the hundreds of feet; the deep gold-quartz veins were certainly formed many thousands of feet deep.[70] Indeed, the depth of formation of many of these gold-quartz veins must have been several miles; and, as above noted, the basic dike rocks associated with these have the same general time relation as in the case of ore found at intermediate depths or near the surface.

It appears, then, that not only the granites and the ore magmas, but probably the basic magmas as well, consolidated at a relatively low temperature, even to great depths. At such depths the normal rock temperature which existed before the magmatic intrusions and after their consolidation must have been less than these estimates; so that there appears, on geological lines of evidence, no indication of rapid normal increment of heat in depth, and, indeed, if the data given above are considered, no evidence of any marked increment at all. Certainly the greatest depths that we can plumb with our ore-zone and igneous-rock

[69] The Ore Magmas, vol. 2, p. 557.
[70] The Ore Magmas, vol. 1, pp. 293, 294.

thermometers must have had a temperature of less than 500 to 600 degrees centigrade before igneous invasion.

THE EARTH'S INTERNAL TEMPERATURE

It has usually been assumed that there was a regular increase of heat from the surface to the center of the earth, based upon the observed increment in shafts and drill holes. This increment, as a matter of fact, is variable, but is most often taken at about 1 degree centigrade for each 30 meters, or nearly 100 feet; or 1 degree Fahrenheit for each 60 feet. If this rate of increment continued to the center of the earth, the temperature there would be about 350,000 degrees Fahrenheit—a conclusion which has been accepted by some.[71]

Following up the planetesimal hypothesis, the central temperature of the earth, if produced by condensation, had been calculated by Lunn[72] at practically 20,000 degrees centigrade. The temperature gradient has been accepted as controlling by Williamson and Adams,[73] who state that "'from the known temperature gradient at the surface, it follows that the temperature at 100 kilometers depth must be considerably above the melting point of ordinary rocks, and it seems unlikely that the central temperature can be less than several thousand degrees." On the other hand, Iddings[74] concludes that "it is quite possible that the temperature of the interior of the earth is not greater than that of the hottest volcanic lavas at its surface, from 1,000 to 1,500 degrees centigrade. Temperatures higher than these are purely hypothetical." And F. W. Clarke[75] concludes that the temperature of the core of the earth, which he assumes to be a metallic mass more than 6,000 miles in diameter, should be nearly uniform and below the melting point of iron, or 1,600 degrees centigrade.

Professor Clarke also observes (page 78):

> "The assumption that temperatures within the earth increase regularly with depth is based upon a very short range of observation. In deep wells and other borings the temperature increases, but not to the same extent in all localities, the average amount being about 1 degree Fahrenheit in 60 feet. The actual measurements are limited to depths of only a little more than a mile, and by extrapolation the conclusion has been reached that at the center of the earth the temperature must be high enough to pass the critical temperature of all known substances. The temperature of the sun, which is now well fixed at something like 6,000 degrees centigrade, would thus be exceeded many times over. Extrapolation sometimes leads to very surprising conclusions."

[71] Grabau: Textbook on Geology, 1920, part I, p. 6.
[72] Chamberlain and Salisbury: Geology, vol. II, New York, 1906, p. 100.
[73] Jour. Wash. Acad. Sci., vol. xiii, no. 19, 1923, p. 420.
[74] The Problem of Volcanism, 1914, p. 156.
[75] Prof. Paper, No. 132-D, U. S. Geol. Surv., 1924, p. 79.

It is needless to point out that my conclusions above are sympathetic with those of Iddings and Clarke.

Mingling of basic Rock Magmas and Ore Magmas

The conclusion that the freezing temperature of basic rock magmas is about the same as that for the ore magmas, while that for the intermediate and siliceous rock magmas is higher, involves the conclusion that on occasion basic rock magmas and ore magmas may freeze more or less simultaneously in a somewhat mixed or mingled form, as well as with the sharp-cut distinction which has been noted in the cases described. This is illustrated not only by the "spotwise" sulphides in the quartz norite at Sudbury, but by many special examples, such as the nickel ores described by Lindgren and Davey[76] at Key West, Nevada, where pre-Cambrian peridotite (enstatite-mica picrite) dikes contain magnetite, pyrrhotite, and chalcopyrite in sufficient volume to form a nickel ore. Of the sulphides, the authors state: "We believe that they formed part of the magma of the dike and consolidated as the last of the minerals of igneous origin." In the same issue of Economic Geology is the paper by Paul F. Kerr, on "Magmatic sulphide ore from Alaska," which describes nickel ore from Chicagof Island. The ore occurs in gabbro at or near the contact with schist, and consists of pyrrhotite, pentlandite, and chalcopyrite, like the Sudbury ores. According to the author, the crystallization of the gabbro first took place, after which pyroxene was altered to hornblende, and this was followed by the introduction of the ore minerals, and finally the development of tremolite.

> "The alteration of the gabbro by hornblende is probably a late magmatic stage, and, according to the views of Tolman and Rogers,[77] is a common phenomenon observed in magmatic sulphide ores. They also state that a subsequent hydrothermal alteration of the ore minerals to tremolite is not uncommon in such ores. Thus it seems reasonable to conclude that the ore is 'magmatic' and the tremolite is a later and probably a hydrothermal alteration."

While these two examples are almost alike, in the former the sulphides are held to have crystallized as part of the original rock fabric, while in the latter they are held to have crystallized distinctly later than the silicates. Since the igneous rock (picrite—only 24.88 per cent SiO_2) in the former case was much more basic than in the latter (gabbro), it is pos-

[76] Econ. Geol., vol. xix, Nov. 4, June-July, 1924, p. 369.

[77] F. C. Tolman and A. F. Rogers: "A study of the magmatic sulfid ores." Stanford University Press, 1916.

sible that a slightly lower freezing point in the former case determined the closer contemporaneity with the sulphide crystallization (freezing).[78]

Relation of Differentiation to Temperature

From the above considerations it may be concluded that any intrusion which shows differentiation was intruded into a horizon where the temperature was, and remained for some time, above the freezing temperature of the magma, inducing magmation or differentiation; and that any intrusive rock which shows a homogeneous crystallization represents a horizon of intrusion where the temperature of the intruded rock enforced prompt freezing or crystallization. Therefore the occurrence of a dike which has cooled promptly and without differentiation would seem to indicate that the rocks into which it entered were hot enough so that the magma did not freeze before it ascended so far; cool enough so that the magma froze promptly, and therefore before it ascended much farther; in other words, had a temperature a little lower than the freezing temperature of the magma, but not much lower.

Ore Deposits in basic Rocks

Consideration should be given to the question why ore deposits do, as recorded, occur in and near basic igneous rocks in depth, while superficial basalts are so characteristically barren.

In the case of batholiths or any other large intrusive mass, those of siliceous nature will, at the freezing stage, be hotter than the freezing stage of the various metal zones. If the temperature is well sustained, as it would be in the case of a large batholith at great depth, there will result an orderly succession of simple and typical metal zones, widely spaced, above and away from the batholith; but if the crystallizing period is accompanied by a more rapidly falling temperature, as in the case of smaller magma intrusions at an only moderate depth, then we have a migration downward of the isogeotherms during the period of crystallization, so that not only is one zone of ore deposition superimposed on another, but the ore zones are superimposed on the igneous rock—that is, they occur in the igneous rock itself.

But in the case of large basic intrusions in depth the tendency will be for the higher-temperature ores, such as chromite and nickel, to crystallize normally near or in the rock-mass, since both crystallize at not far from the same temperature and since the crystallization process is a slow

[78] Compare p. 567.

one, while the lower-temperature ore zones, such as copper, and especially lead, zinc, and silver, are being deposited above; and if the isogeotherms migrate downward during the crystallization period, these lower-temperature ore zones will be superimposed on the basic igneous rock and form veins and other epigenetic ore bodies in or near the basic rocks. But in the case of basic rocks very close to or at the surface, such as the basaltic lavas, it seems that refrigeration takes place so suddenly that the critical isogeotherms of the metal zones pass immediately to a greater depth, where the ore deposits will ordinarily be formed, if at all.

The above may also explain why large areas of siliceous igneous rocks, such as granites, are characteristically poor in ore deposits, which are more characteristic of their aureoles; but the same is not true of the smaller bodies of siliceous igneous rock, which have cooled more rapidly, either because of a lesser depth or a lesser volume of magma. These rocks, the siliceous and the intermediate porphyries, are characteristically associated with ores and are a favorite wall rock for mineral veins. Moreover, the siliceous and intermediate superficial rocks, the rhyolites and andesites, maintain, even after consolidation, a temperature corresponding with the metal isogeotherms for an appreciable time, sufficient to enable them to be the host rock for mineral veins.

Amount of Temperature Reduction by Gases

The fact being conceded that magmas remain fluid at relatively low temperatures on account of the gaseous ingredients, the question arises as to the amount of gaseous constituents necessary to establish this condition. It has long been recognized that the granite magma remained fluid by this means; but this has not been so well comprehended for the basic magmas. Yet, since there are transitions from one into the other, through intermediate phases, and no sharply drawn boundaries, the universal presence of the gaseous elements as an essential constituent of any magma is to be assumed; and this is confirmed not only by the gaseous effluvia of basic lavas, but by the contact phenomena of basic intrusions, which indicate the exhalation of gases on consolidation, at the same time that they indicate a far less content of volatile ingredients than the siliceous magmas contain. Yet our conclusions above would indicate that the minor proportion of volatile constituents in the basic magmas is as effective in maintaining fluidity to low temperatures as in the larger proportion in the siliceous magmas; so that, beyond a certain limited amount, these gaseous constituents would seem to be superfluous, so far as the effect of maintaining fluidity at relatively low temperature is con-

cernel.[79] The surface temperature of the Hawaiian basalts is around 1,200 degrees centigrade, as above stated, with the evidence that in depth the temperature grows less; and for certain dike rocks of this type I have inferred above a freezing temperature of around 500 degrees centigrade; but experiments in fusing the Palisade diabase of New Jersey (an augite-plagioclase rock with a little olivine)[80] shows that it begins to fuse at 1,150 degrees centigrade and becomes completely liquid only at 1,300 degrees. If the above tentative conclusions are right, the lowering of the freezing point of basic rocks from, say, 1,300 degrees to 500 degrees, an amount of 800 degrees centigrade, has been accomplished by the presumably small percentage of contained volatile constituents. Granite becomes fluid or viscous at a higher temperature, possibly 100 or 150 degrees or so more than that of basic rocks;[81] this would give an empirical figure of 1,450 degrees to compare with the freezing temperature of granite magmas of 600 to 700 degrees assumed on page 563—a difference of 750 to 850 degrees. In view of the uncertainty of these figures, we can only say that all considerations indicate that the smaller proportion of volatile ingredients of basic magmas reduces the freezing temperature by about the same amount, or nearly the same amount, as the larger proportion does in siliceous magmas. This conclusion, that a relatively small amount of gases sufficed to establish great magmatic fluidity, I reached some time ago for the ore magmas,[82] observing that:[83]

"In view of the evidence of a very widely varying amount of water and other gases like fluorine, boron, etcetera, while metallic sulphide deposition remains constantly heavy, there is demonstrated the fact that water and these gases, the abundance of which has long been supposed to be the *sine qua non* of ore deposition, are really necessary, if at all, only in very small relative amounts."

Wall Rock heating by Gases

Another important supplementary consideration is the possibility that consolidating magmas raise the temperature of their wall rocks by chemical reactions set up among the magmatic gases penetrating the wall rock. If the chemical reactions set up by the gases released by the rock magmas as they come very close to the surface contact of the magma will raise the temperature of the magma far above the normal condition, as believed by

[79] This necessary "limited amount" is, however, evidently considerably greater for the siliceous magmas than for the basic magmas.

[80] Sosman and Merwin: Jour. Was. Acad. Sci., vol. iii, no. 14, 1913, pp. 389-395.

[81] Daly: "Igneous Rocks." McGraw-Hill Book Co., 1914, p. 213. Sosman and Merwin, op. cit., p. 394.

[82] The Ore Magmas, vol. ii, pp. 523, 625, 709.

[83] Op. cit., p. 625.

Day and Shepherd,[84] it is likely that similarly heat is locally evolved by the reactions along the contact between the magma and intruded rocks in depth, when in the act of consolidation the magma gives off its gases. It is also likely that this heating would be especially characteristic of the more gaseous magmas and, indeed, to a larger degree of granitic than of basic magmas. As has often been mentioned, the granites show much more evidence than the basic rocks of powerful contact reactions, which have metamorphosed and metasomatosed the rocks they intrude, sometimes through a broad bordering zone. This reheating would affect the intruded rock and also the marginal zone of the intrusive magma body, but chiefly the former. Thus the temperature of formation of contact metamorphic minerals may be in part higher than that of the freezing of the attendant intrusive magma. If this is true, it is evident that a crystallized igneous rock, basic or siliceous, may later be raised by some incident (such as the near approach and consolidation of a great batholith below) to a higher temperature than that at which it originally crystallized.

Summary

It has come to be widely accepted that the frequent zonal arrangement of different metals in concentric rings up and away from a given igneous center indicates that each metal has been crystallized in its own specific zone of temperature from a mixed ore solution or ore magma migrating away from the central seat of differentiation. This conclusion would imply that in each zone the wall rock of lodes characterized by a certain metal was at the time of ore injection hot enough to allow penetration by the metal solution in question, cool enough to prevent its traveling farther before consolidation; in other words, that it had a temperature close to that of the freezing temperature of the metal solution in question. Pegmatites and pegmatitic ores, including those of tin, tungsten, and molybdenum, have probably crystallized below 575 degrees, but not very much below; hence the wall rock of pegmatitic veindikes will typically have had a temperature, roughly speaking, somewhat below this point. As to rock magmas, it seems probable that the magma of very thin dikes at least have also been sensitively controlled as to their locus of freezing and have been crystallized by wall rocks which had a temperature close to their freezing point. Since the metal zones have a regular succession which is shown in many different regions, as the distance from the igneous center increases, they are markers of falling temperature and may be taken as

[84] Op. cit., p. 299.

graded geologic thermometers, affording a relative measure, even if not exact determinations. They may thus indicate the temperature of rocks in the different zones where they have selectively crystallized.

Ordinarily ore intrusion constitutes the last of the magmatic injections in a given igneous center, which center is very often marked by evidences of magmatic differentiation. But there are frequently recurring cases where scanty dike injections are contemporaneous or even later than the ore injections. These latest rock magma injections are so often basic dikes, in part lamprophyric, as to attract attention and examination of the data.

First, as regards deep-seated gold-quartz veins (which usually have a main low-grade quartz stage passing into a later higher-grade sulphidic stage), an example is Silver Peak, in Nevada, where trap dikes cut the quartz veins, but before completion of the sulphide mineralization, and so were essentially contemporaneous with the ore magma injection. The gold-quartz veins of north central Idaho have the same relation to basic dikes as at Silver Peak. At Porcupine, in Ontario, the gold-quartz veins are followed by diabase dikes. At Kirkland Lake, Ontario, the gold veins (which, unlike the three cases cited above, are not veindikes) are partly contemporaneous in their later stage with diabase dikes. In Inyo County, California, a gold lode is cut by later lamprophyric dikes, and in the Tangier district of Nova Scotia a gold-quartz vein is intersected by a later "dioritic" dike. The gold-quartz veins of Victoria, in Australia, are most commonly related to lamprophyre and to diorite porphyry dikes.

Turning now to nickel-copper ores: At the Worthington mine, in Sudbury, trap dikes were intruded contemporaneously with the last stage of injection of copper-nickel sulphide; the trap was followed by olivine diabase dikes, and these were followed by blende-galena veins; so that in a general way the ore magmas and the basic rock magmas were contemporaneous.

Passing to copper camps: At Rossland, in British Columbia, lamprophyric dikes were contemporaneous with copper-bearing veins.

At Jerome, in Arizona, during the copper mineralization period, small diorite or andesite dikes were intruded.

In the Ainsworth district, in British Columbia, galena-blende ores are practically contemporaneous with lamprophyre (camptonite) dikes.

At Wallace, Idaho, zinc-lead veins are cut by later diabase dikes. The lead-silver ores of Mapimi, in Mexico, were introduced after an alaskite intrusion, and were followed by a diorite intrusion.

These cases, which might easily be multiplied, lead to the suggestion

that the temperature of consolidation of these basic dikes corresponded nearly to that of the ore magmas.

Considering Tertiary ore districts: At Cripple Creek, in Colorado, the latest dike rocks in a differentiation series were basaltic, including limburgite, and these immediately *preceded* the introduction of the (gold) ores. At Silver Cliff, in Colorado, the last igneous rock in a differentiation series was basic—limburgite; and this immediately *succeeded* the (zinc-lead-silver) ores. At the Braden mine, in Chile, in an igneous differentiation series successively injected, copper ores were introduced at two distinct and definite general periods; and the last period was *succeeded* by a lamprophyre dike, as at Silver Cliff; this dike closed the magmatic sequence. At Braden, as at Cripple Creek and Silver Cliff, the basic dike magma and the ore magma seem to have been nearly contemporaneous. At Braden, dacite and latite (and granite) porphyry were intruded between the two main periods of copper introduction, and might therefore appear at first glance to have congealed at the temperature of the copper consolidation. Not so, however; for these siliceous magmas solidified almost completely at a greater depth and therefore probably a higher temperature, and were forced up to their present horizon in intimately brecciated form by the pressure of the still fluid magma below. This is different from the lamprophyre, which consolidated entirely at this horizon; hence we may believe that while the freezing temperature of the basic rock was about the same as that of the copper ore magma, the siliceous intrusions had a somewhat higher freezing temperature.

Considering all these cases, I conclude that these ultimate basic dikes may have consolidated around 400 to 500 degrees centigrade, which I have estimated, following various clews, to be about the range of temperature of the copper-zinc-lead zones. All these crystallize at a lower temperature than the pegmatites, whose quartz, as determined by Wright and Larsen, formed below 575 degrees centigrade, while the quartz of granites crystallized above 575 degrees, suggesting a temperature of crystallization for the granites or granite porphyries of, let us assume, 600 to 700 degrees. Lamprophyres are basic dike rocks, usually high in hornblende or biotite. They are silica-poor products of differentiation, whose intrusion has been held in many instances normally to follow that of the aplites. The mineralizers, especially H_2O, have been held to play a special rôle in their differentiation. But while many of the basic dikes which are essentially contemporaneous with ores, in the instances I have cited, are lamprophyres, according to the above definition, others are not, being simply "trap" or diabase, including olivene diabase. The dikes in

question range, indeed, from diorites to diabases, and to special mineralogical types; so that if we conclude that their temperature of consolidation was around 400 to 500 degrees centigrade, as above, we are bound to suspect that the basis magmas in general consolidate at that temperature in depth. We can understand that these basic magmas may have remained fluid at this relatively low temperature largely on account of the gaseous magmatic elements present—an explanation which has long been used for the evidently low temperature (600 to 700 degrees) of crystallization of granitic magmas.

Basaltic lava at Kilauéa has a surface temperature of about 1,000 to 1,200 degrees centigrade. Day and Shepherd found various magmatic gases, including water, escaping, and found that heat was generated by the interreactions among these gases; so that they suggested that lava may become hotter, and not cooler, as it approaches the surface.

If it is true that the surface temperature of congealing basic lavas (and, indeed, siliceous lavas) is about twice the freezing temperature of the same magmas in depth, how deep does the surface heat go? I have pointed out that ore magmas seem to have a "dumping horizon," not at the surface, but at a depth of, say, 500 to 1,000 feet below it, and have argued that at this horizon the gravity pressure is no longer sufficient to overcome the gaseous tension of the volatile components of the ore magma, which thereupon escape; so that the ore magma disintegrates and the solid portion is thrown down regardless of temperature. It may well be that at this same horizon, or somewhat lower, the gases begin to escape from the lavas. On this reasoning the lower temperatures of rock magmas may obtain from this critical horizon downward, while the temperature rises from this horizon to the surface.

As to the depths to which these assumed moderate normal temperatures of, let us say, 400 to 500 degrees for basaltic magmas and 600 to 700 degrees for granitic magmas, are characteristic, we may recall that pegmatites, which are generally held to have frozen below 575 degrees centigrade, are characteristic of the greatest depths revealed by erosion; therefore they indicate in general wall rocks as cool as or cooler than this temperature; also, the well recognized zones of metal deposition which follow the pegmatite zone occur apparently in a uniform sequence, from relatively slight depths to the most profound of which we have record. It appears, then, that not only the granites, pegmatites, and metallic ores, but probably as well the basic igneous rocks frequently accompanying the ores, consolidated at a relatively low temperature, even to great depths.

Thus there appears, on geological lines of evidence, no indication of a

continued increment of heat in depth. Certainly the greatest depths that we can plumb with our ore-zone and igneous-rock thermometers must have had a temperature of less than 600 degrees centigrade before igneous invasion.

Geologists, physicists, and chemists have differed widely in the views as to the heat at the center of the earth, varying from an estimate of several hundred thousand degrees, as calculated by Arrhenius and accepted in Grabau's textbook, to F. W. Clarke's statement that the central temperature must be below 1,600 degrees centigrade. It is needless to say that my conclusions above are sympathetic with Clarke's views.

Why, then, if the more basic rock magmas have about the same freezing temperature as the ore magmas, and since relatively higher temperature ores, such as copper and nickel, accordingly crystallize in depth almost contemporaneous with or a little later only than basic rocks—why, then, do we not find similar ones, at least, in the superficial basalts? It is a fact that we do not. Nickel, for example, does not occur in Tertiary volcanics,[85] and, indeed, the Tertiary basalts are notoriously barren of all ores. It is likely that the crystallization of basalt is so rapid that the isogeotherms immediately drop below those of the ore-magma range, and that the ores will accordingly be found below, if at all; while the siliceous and intermediate lavas retain for some little time after consolidation temperatures sufficient to allow the penetration of ore magmas.

If the above considerations are true, that the decidedly basic magmas freeze in depth at about the same temperature as the ore magmas, it would seem to follow that in large masses of differentiating basic magmas in depth the ore magmas would crystallize at about the same temperature, and hence at about the same time and place, as the rock magmas. This in distinction from the siliceous rock magmas, in regard to which the ore magmas would crystallize at a lower temperature, and therefore generally at a different time and place. This may result in basic silicate magmas and ore magmas freezing in a mixed or mingled form, which is illustrated by the sulphides which occur spotwise in the quartz norite at Sudbury, and by many other cases where the metallic minerals are abundant enough in basic dikes to form ores. It appears to be the rule, however, that in these cases the sulphides crystallize later than the silicates—a difference which may be more or less marked.

Apparently, therefore, the minor proportion of volatile constituents in the basic magmas is as effective in maintaining fluidity to low temperatures as is the larger proportion in siliceous magmas. Experiments on

[85] The Ore Magmas, chap. II, p. 614.

the fusibility of diabase and granite (the former of which has in certain instances been fused around 1,300 degrees centigrade and the latter around 1,450 degrees) give temperature points which, when compared with the conclusions as to the freezing temperatures of the magmas in depth, suggested in this paper, would indicate that the volatile constituents had lowered the congealing point by about 800 degrees in each case.

A supplementary suggestion is that in the wall rocks of consolidating magmas the released gases, by their exothermic interreactions, may raise the temperature higher than that of the cooling point of the magma itself, so that minerals thus crystallized in the wall rocks may have done so at a higher temperature than the normal constituent minerals of the igneous rock. This would, perhaps, be more marked in the case of siliceous plutonic magmas than basic ones, on account of the greater quantity of exuded gases.

TABLE OF BASIC DIKE SEQUENCES

A. Relative to Gold Ores

Silver Peak, Nevada	North Central Idaho	Porcupine, Ontario
1. Granite.	1. Granite.	1. Quartz and syenite porphyries (sheared).
2. Alaskite.	2. Pegmatite.	2. Quartz veindikes (gold).
3. Quartz veindikes (gold).	3. Quartz veindikes (gold).	3. Augite diabase.
4. Diorite.	4. Diabase.	4. Olivine diabase.
5. Sulphides and gold.	5. Sulphides, gold and silver.	

Kirkland Lake, Ontario	Nova Scotia	Inyo County, California
1. Syenite, etcetera.	1. Granite.	1. Granite.
2. Quartz replacement veins (gold).	2. Quartz veindikes (gold).	2. Gold ores.
3. Olivine diabase.	3. Diorite.	3. Lamprophyre.
4. Sulphides and gold.		

Cripple Creek, Colorado

1. Latite porphyry and phonolite.
2. Basic dikes.
3. Sulphide ores (gold-bearing).

B. Relative to Nickel-copper Ores

Sudbury, Ontario (Creighton mine)	Sudbury, Ontario (Worthington mine)
1. Diorite.	1. Norite.
2. Granite.	2. Sulphides (nickel-copper).
3. Sulphide veindikes (nickel-copper).	3. Trap.
4. Diabase.	4. Diabase.
5. Olivine diabase.	5. Sulphides (lead-zinc).

C. Relative to Copper

Rossland, British Columbia	Jerome, Arizona	Braden Mine, Chile
1. Monzonite, etcetera.	1. Quartz porphyry.	1. Andesite porphyry.
2. Sulphide veins (copper-gold-silver).	2. Diorite.	2. Sulphides (copper).
3. Lamprophyre dikes.	3. Sulphide ores (copper).	3. Dacite-latite.
4. Sulphide veins (copper-gold-silver).	4. Diorite dikes.	4. Granite porphyry.
	5. Sulphide ores (copper).	5. Sulphides (copper).
		6. Lamprophyre dike.

D. Relative to Zinc-lead-silver

Ainsworth, British Columbia	Wallace, Idaho	Pend d'Oreille, Idaho
1. Granite.	1. Monzonite.	1. Quartz veins.
2. Sulphides (zinc-lead-silver).	2. Pegmatite and quartz veindikes.	2. Sulphides (zinc-lead-silver).
3. Lamprophyre dikes.	3. Sulphides (zinc-lead-silver).	3. Lamprophyre dikes.
4. Sulphides (zinc-lead-silver).	4. Diabase dikes.	

Silver Cliff, Colorado

1. Andesite.
2. Dacite.
3. Rhyolite.
4. Andesite.
5. Trachyte.
6. Sulphides (zinc-lead-silver).
7. Basaltic dike.

Discussion

Prof. James F. Kemp: Mr. Spurr's paper is one of great interest and pushes one more stage ahead our progress in the interpretative attitude of observers today toward veins. Regarding the temperature of the consolidation of igneous rocks in depth, I have also pondered somewhat upon the results of Dr. A. L. Day's discovery that the temperature of the Hawaiian basalt at Kilauéa was less below the surface of the molten mass than at the surface, and that the melting temperature might be produced by the reactions of the escaping gases. On the other hand, we have believed for many years that increasing pressure with depth raises the fusing point, and that progress toward the surface, with diminishing pressure, lowered it. While we have realized that dissolved gases might also lower it as compared with so-called "dry" fusion, yet, at least in the case of the rocks without gases, one finds difficulty in believing that deep-seated or moderately deep igneous rocks do not require higher temperatures for fusion than those at the surface. That rocks are molten at impressive depths, and sometimes apparently as fluid as water, is shown by the case of the basaltic dike recorded by T. A. Rickard in the 180 mine, which is based on saddle-reefs of gold-bearing quartz in the Bendigo dis-

trict of Victoria, Australia. The dike, uniformly about 9 inches thick, has been followed in a somewhat zigzag course vertically downward for 2,600 feet. An unknown portion has been removed by erosion. Such a dike must have been extremely fluid.[86]

Regarding the escape of vapors and solutions from igneous magmas at depths from 1,500 to 500 feet, and subsequent deposition of ores such as galena, I might cite the case of the enormous bodies of silver-bearing galena with a gangue of siderite which have been opened in the Bunker Hill and Sullivan mines, in the Cœur d'Alene district of Idaho, and which must lie 2,000 feet or more below the present top of the mountain. The country rock is pre-Cambrian quartzite, and the ores are generally believed to be connected in their formation with intrusive granodiorite. We must allow something for erosion. I think we can not escape a much deeper source of the solutions or vapors than 1,500 feet. I think crystallization of a magma to anhydrous silicates evicts dissolved vapors and potential liquids at much greater depths.

Mr. Spurr's paper has been of special interest to me because of studies of dikes extending over many years.

[86] See Trans. Amer. Inst. Min. Eng., vol. 20, 1891, p. 485.

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DENTITION OF ARTIODACTYLS[1]

BY F. B. LOOMIS

(Read before the Paleontological Society December 30, 1924)

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INTRODUCTION

The artiodactyls are a group of hoofed mammals set off from the others primarily by the tendency to reduce the foot to the third and fourth digits. The earlier forms may have four toes, occasionally a trace of the fifth, but in all cases the weight falls between the third and fourth digits, so that they are equally developed, and there is no possible tendency to develop a single-toed foot, as in the perissodactyls. At its maximum development this makes the "cloven hoof," which is never a cloven hoof, but the incomplete fusion of the two above-mentioned digits. This group is also characterized throughout by the astragalus bone in the ankle having a roller surface on its lower end as well as the usual roller surface on the upper end—an astragalus which is unique. The group includes a wide range of animals, some but little specialized, like the pigs; others among the most specialized living forms, such as camels, deer, and antelopes. In these latter types the feet have gone to the limit of specialization for the group—two toes, fused metapodials, reduced fibula and ulna—and at the same time many have acquired highly specialized structures, like the camel's hump, the antlers of deer, the horns of cattle, and the complex several-compartment stomach of ruminants. Some of these structures have even been so far developed as to raise the question of

[1] Manuscript received by the Secretary of the Society June 15, 1925.

whether they have not become a handicap to their possessors. At the present time the group is apparently at its maximum development, having a wealth of genera and species, as well as a wealth of individuals, equaled by no other group of larger mammals.

In spite of the great numbers at present living and known from the past, the ancestral relationships and lines of development are less satisfactorily worked out than in any other group. This is due in part to lack of fossil material, but much more to the striking uniformity of the teeth in such different forms as deer, camels, goats, sheep, and cattle. The pig phyla (Suidæ) are readily separated from the others by the teeth being crowned with low, rounded cusps (bunodont), and apparently these forms represent an independent evolution from a very early date.

Then there is a number of families of small to medium-sized animals, all extinct, which are characterized by the premolars, and to some extent the molars, being bunodont, while at least the outer cusps on the molars are crescents extending from front to back. These are the bunoselenodonts (Dichobunidæ, Anoplotheriidæ, Anthracotheriidæ, etcetera), which appear first in early Eocene and die out in the Oligocene. Neither of these groups show that peculiarity which is common to all the later forms—that is, having the lower canine modified to an incisor in form and function, while the first lower premolar takes on the form and function of a canine. This character is common to the oreodonts, camels, deer, sheep, cattle, and antelopes and is indicative of common origin. With it goes the fact that the molars are crowned by four cusps, all consisting of crescent-like ridges running from front to rear and more or less united to one another. These make up the great group of selenodonts. The having of cusps which run from front to rear, instead of transversely across the tooth, is what makes the term selenodont and what is characteristic of artiodactyls.

This homogeneity in the character of the molars makes clear the unity of the relationship of the selenodonts, but at the same time it has been the barrier which has prevented the solving of the phylogenetic relationships within the group. During the last fifty years the molars have been the most useful structures for determining the phylogenetic relationships; for on the one side they are conservative in retaining the group plan, and on the other side they are very quick to take on new characters, because they are so closely related to that most fundamental function, getting of food. In this group the molars are too uniform, and as a result students have turned to such structures as antlers and horns. Unfortunately, these are not highly essential structures, nor so related to any

of the fundamental habits as to register changes of habit. In fact, they are so unessential that they may be present in one sex and lacking in the other, present in one species and lacking in another very closely related, and may vary greatly without corresponding variation in the rest of the body. While useful for details and confirmation, I feel they are deceptive as guides to phylogeny.

In studying a group which did not have any of these accessory structures, the oreodonts, I was thrown back into the dentition, where I found[2] that, in spite of the uniformity of the molars, there was as great variation in the premolars from one genus to another as is characteristic of the molars in other groups. Not only this, but it appeared also that the manner in which that peculiar upper premolar, number 4, was formed was different from the manner in which the same tooth was formed in other phyla, as deer or camels, for instance. This led me to a comparison with as many and as varied selenodonts as possible, to see if the various modes of formation of premolar number 4 were uniform for the various phyla, and if the differences were constant; also, if there was a relationship between the bunoselenodonts and the selonodonts. For this purpose I have studied the dentitions of some 200 genera and come to some definite general conclusions: First, that the selenodonts are not derived from the bunoselenodonts, though of common origin; second, that each main phylum, such as deer, camels, bovids, gazelles, etcetera, has acquired its peculiar fourth upper molar in an independent manner, and therefore that these phyla are independent from an early period; third, that the premolars, especially the lower premolars, register phyletic and generic characters, by which not only can the phyla be distinguished, but also the position in the phyla determined; and, lastly, that by the use of the premolars and such characters as are developed in this paper such tangled groups as cattle, deer, and antelopes can be straightened out.

Development of the Selenodont Type of Teeth

First of all, the selenodonts are peculiar in the modification of lower premolar 1 to a canine function and shape; so, when the teeth were modified to be used as grinders, there were seven teeth (three molars and four premolars) in the upper series to act against six teeth in the lower series (three molars and three premolars). The result is a tendency to shorten the upper series and at the same time to elongate the lower series. The upper series is shortened by the reduction of premolar 4, so that it usually

[2] Bull. Amer. Museum Nat. Hist., vol. II, 1924, pp. 1-37.

appears like a half molar (see figure 1-A). The lower series elongates by the addition of a third lobe on the rear of molar 3, both of these characters being typical of this group. The ways in which the fourth upper premolar is reduced are several, and these ways are what is characteristic of the various phyla. In some the anterior portion of the tooth is lost; in others it is the back half which is lost, and in still others the tooth is shortened by compression from front to back. Into this I will go in detail further on.

The homologies of the various cusps on the premolars and molars is so different from those postulated by the tritubercular theory that, to avoid

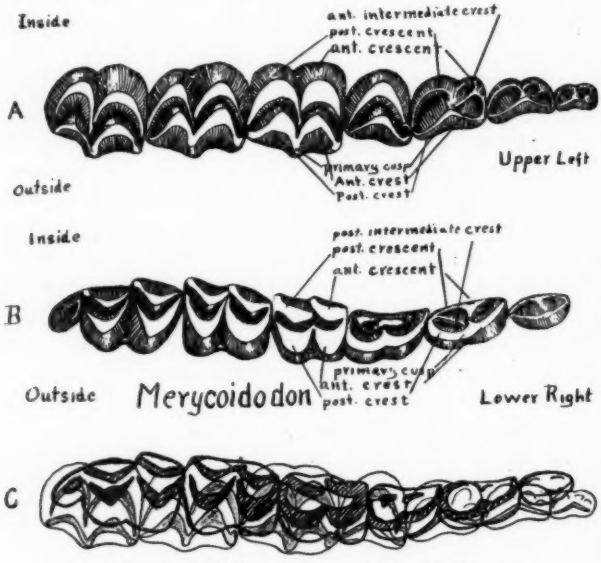

FIGURE 1.—*Dentition of Merycoidodon culbertsoni*
A, upper; B, lower; C, occlusion. Natural size.

confusion, I would use a descriptive nomenclature for this whole group. In getting at the homologies I have used the premolar-analogy method, from which we get the following (see figure 1).

The most typical tooth from which to start to make comparisons with either the teeth in front of it or those behind is premolar 3. The high median cusp I would call the primary cusp. From it there is a ridge to the front, the *anterior crest*, and one to the rear, the *posterior crest*. On the inner side, over the anterior root, is a cingulum, in varying degrees of

development, which, when enlarged, becomes the *anterior crescent;* and, in like manner, over the posterior root is the *posterior crescent.* These are the four chief parts of a selenodont tooth. There may be, and generally are, one or more ridges on the premolars which extend from the primary cusp to or toward the crescents. When present, I term the one from the primary cusp toward the middle of the anterior crescent the *anterior intermediate crest;* the median ridge the *median crest,* and the ridge from the primary cusp toward the posterior crescent the *posterior intermediate crest.* These last named crests seldom appear on the molars.

Comparing the premolars and molars, the anterior external cusp is seen to be the middle of the anterior crest; the posterior external cusp the middle of the posterior crest; so the primary cusp of the premolar, if represented on the molar, must be the mesostyle. On the lower molars these external cusps are crescentic in shape, and the primary cusp is either entirely lacking or represented by the median style. The anterior internal cusp is very clearly the anterior crescent, and the posterior internal cusp is the posterior crescent. The cingula on the premolars start from the anterior or posterior ends of the tooth; so that when developed into crescents these seem to spring from the front and rear and meet in the middle of the tooth.

A careful consideration of figure 1 will show how crests and crescents arise and grade into the molar cusps. It is to be noted that in all figures the upper left molars are given and the lower right, so that by transferring an outline of any upper series directly over the corresponding lower series a diagram of the occlusion is obtained, as in C of figure 1. This diagram of the occlusion brings out the effective way that these crescent-shaped cusps work against each other when a lateral motion of the jaws is used in rumination. In all figures the upper side is the inner side and the lower side is the outer side of the dental series.

After considering the dentition of this Oligocene form, the question naturally rises as to whether the earlier artiodactyls have a dentition which conforms to the above. The earliest in both Europe and America are the dichebunids, and the answer must be that its dentition does not conform at all closely.

In figure 2 are given representative upper dentitions of the bunodont and bunoselenodont families. Diacodexis is the earliest genus and has what has been considered the simplest molars. There are three inner cusps, the median one the largest, the other two being interpreted as intermediate cusps, the posterior cusp (hypocone) being absent. In Dichobune this cusp is present and there are six cusps.

Stehlin[3] has pointed out that there are at least three modes by which these inner cusps of artiodactyls arise. He then derives the selenodont type with but four cusps, by the loss of posterior inner cusp (compare figure 3, D), and says that all artiodactyls had originally extra intermediate cusps. These bunoselenodonts do, mostly an anterior intermediate, which is particularly characteristic of the Anoplothers and Anthra-

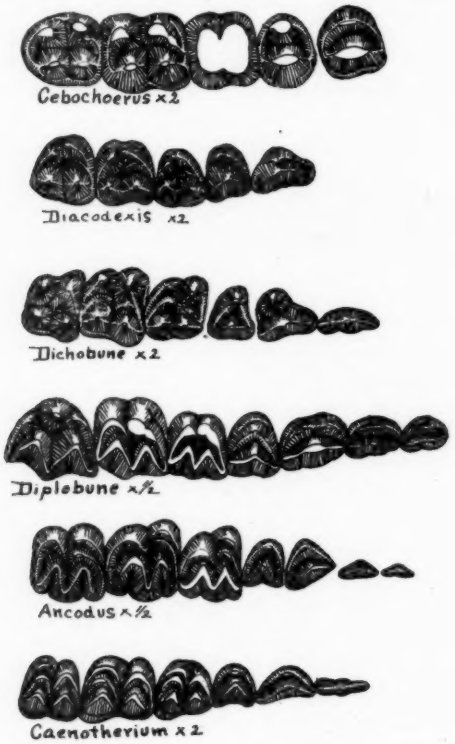

FIGURE 2.—*Typical upper dental Series of Bunodonts and Bunoselenodonts*

Cebochœrus illustrates Suidæ; Diacodexis and Dichobune illustrate Dichobunidæ; Diplobune illustrates Anaplotheriidæ; Ancodus illustrates Anthracotheriidæ, and Cænotherium illustrates Cænotheriidæ.

cotheres, while the Cæonotheres have the extra cusp in the hinder region. My belief is that the cusps have all arisen as a result of the development of the cingulum, and that the so-called "intermediate cusps" are the

[3] Abhand. Schweitz. Palæont. Gesellschaft, vol. xxxvi, 1910, p. 1135.

earlier cusps, to which have been added those on the internal side of the tooth and usually designated as "metacone" and "hypocone."

In figure 3 I have shown a series of five types of upper molars. The first two (A and B) are dichobunids and show progressive development. C is that of an anthrocothere with the anterior intermediate, while D is that of a cænothere with the posterior intermediate. I can see no reason for assuming that the selenodont as illustrated in E is derived from any one of the others. It is the simplest of the whole series. Then all forms with the simple four-cusped type of molar also have the first premolar modified to a caniniform tooth, whereas all these others have it functioning normally. I can not but feel that this peculiarity and the four-cusped molar go back to an early Eocene stock as yet unknown. The

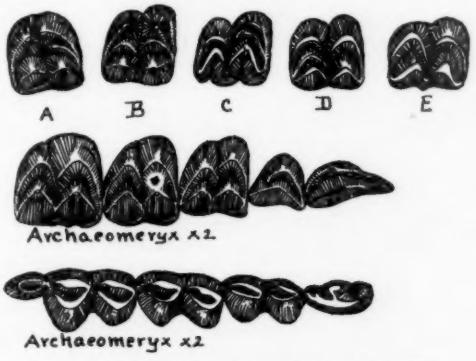

FIGURE 3.—*Two Upper Molars to show Variation*

A, Diacodexis; B, Dichobune; C, Ancodus; D, Cænotherium; E, Merycoidodon. Below, the upper and lower dentition of Archæomeryx, from Shara Marun, Mongolia.

earliest form which shows the characters of the modern artiodactyls is Archæomeryx from Mongolia (see figure 3), and it gives no suggestion of there ever being more than four cusps. It is described as an early deer, though to me it would seem rather more like an antelope or sheep—that is, one of the hollow-horned line; but in any case it is a typical selenodont dentition.

In the case of the lower premolars and molars, as in the upper ones, the primary cusp of the premolar, with its crests forward and backward, gives rise to the outer side of the molars, the anterior crest making the anterior external cusp and the posterior crest making the posterior external cusp, the primary cusp becoming less prominent in the last premolars and disappearing on the molars entirely. The two inner cusps are derived from

the cingula, as in the upper teeth. In the more advanced genera there is a tendency for the fourth premolar to assume molariform character (see figure 6).

Comparisons with Bunodont and Bunoselenodont Dentition

In turning to the bunodonts and bunoselenodonts (figure 4), there are some striking peculiarities which are confined to these families. In

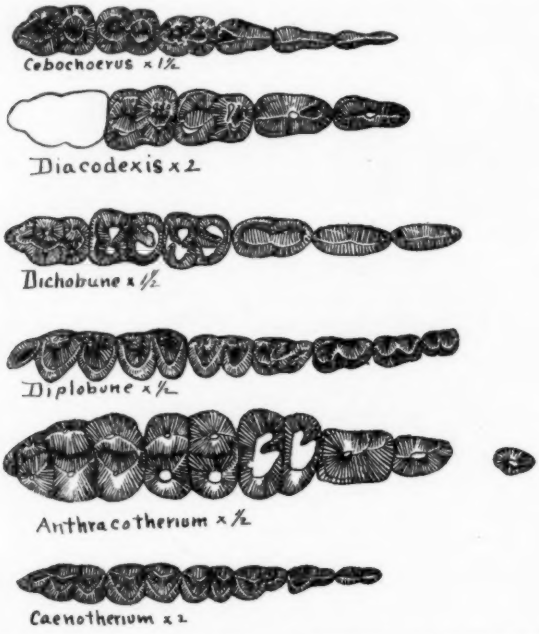

FIGURE 4.—*Typical lower Dentitions of Bunodonts and Bunoselenodonts*

Cebochœrus illustrates Suidæ; Diacodexis and Dichobune illustrate Dichobunidæ; Diplobune illustrates Anaplotheriidæ; Anthracotherium illustrates Anthracotheriidæ, and Cænotherium illustrates Cænotheriidæ.

dichobunids and anoplotheres the outer cusps are developed as crescent-like cusps, while the inner crescents are bunodont cusps. In these also the molars develop so that there are two internal cusps on the anterior part of the tooth and one on the posterior part, making a total of five cusps. In antracotheres, cænotheres, and bunodonts there are but four. Each family seems to have developed its peculiar molar form independ-

ently, and all stand in contrast to the simple four cusps of the selenodonts. This, with the fact that the first premolar is normal in all these families, makes them independent back to some time in early Eocene.

VARIATIONS IN THE METHOD OF FORMING SELENODONT TEETH

Returning to the selenodonts, one of the striking features is the shortening of upper premolar 4, so that it appears like a half molar and is

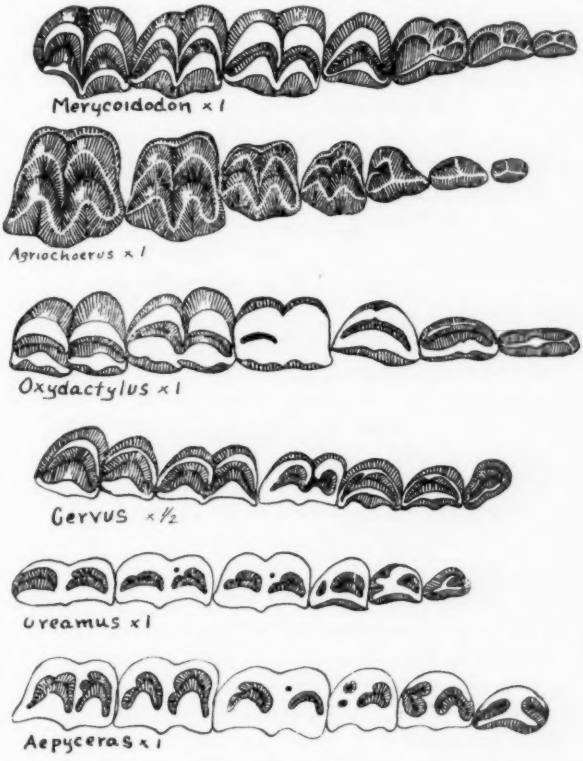

FIGURE 5.—*Comparison of typical upper dental series*

Oreodonts are illustrated by Merycoidodon, agriochœrids by Agriochœrus, camels by Oxydactylus, deer by Cervus, goats by Oreamus, and gazelles by Aepyceras.

shorter than either the tooth in front or behind it. This shortening takes place in different ways in the different phyla. In Merycoidodon and all other oreodonts, upper premolar 4 corresponds to the posterior

half of premolar 3, the anterior portion disappearing. In this genus, and also several others which are primitive, there is a vestige of the anterior basin in the shape of a tiny crescent in the anterior external corner of the tooth. In one case, Oreonetes of the Lower Oligocene, traces of both the anterior basins are preserved.[4] In the later genera of this phylum even this trace is gone. In camels upper premolar 4 attains its character by being shortened from front to rear, the anterior and posterior crescents coalescing near the middle of the tooth (see figure 5). Among the deer, this tooth is also shortened from front to rear, but in this case the anterior crescent overlaps the posterior crescent (as also in the molars), so that there is a spur projecting into the basin of the tooth. Among the goats, sheep, and cattle it is the anterior portion of the tooth which is retained, the rear part being reduced, sometimes completely, sometimes incompletely, as shown in the dentition of Oreamus in figure 5. The gazelles are peculiar in that both front and rear parts are retained and shortened, but the resulting basin is divided by the largely developed median crest, making a peculiar pattern. Agriochœrids are peculiar in that the upper fourth premolar is distinctly molariform.

The lower fourth premolar (see figure 6) is not shortened, and the tooth is transitional in character between the molars and the premolars, in some phyla developing special peculiarities. In oreodonts the intermediate crests are weak or absent, the crescents being variously developed. The camel lower fourth premolar is very simple, only one internal crest being developed, and that apparently the posterior intermediate crest, which tends to unite with the posterior crest and inclose a small basin. All the premolars are compressed from side to side and have the character of the fourth one, but in less degree toward the front. The deer, in contrast to the foregoing, have both the intermediate crests and the median crest well developed on all the premolars. Among goats, sheep, and cattle the internal crescents are developed along with the median and posterior intermediate crests. The fourth premolar of the gazelles has, along with the anterior intermediate, median and posterior intermediate crests, the anterior crescent, but on the other premolars this crescent is less developed.

From the above it is evident that the various phyla have independent methods of developing both upper and lower premolars. While the shortening of upper premolar 4 is universal, the method of shortening it is different in each major phylum. I can not but feel that the same cause has acted on them all, but this cause was not applied until there was

[4] Bull. Amer. Museum Nat. Hist., vol. II, 1924, figure 4.

already a separation of the phyla. This would mean that not only were oreodonts, camels, and deer independent from the beginning of the Oligocene, but that goats, cattle, and giraffes had also parted company with the others and each other not later than early Oligocene, probably back in the Eocene. It is hardly possible to think that, after any one of these methods had started, a jump to one of the others was possible. This way of looking at these phyla emphasizes what has seemed probable—that is,

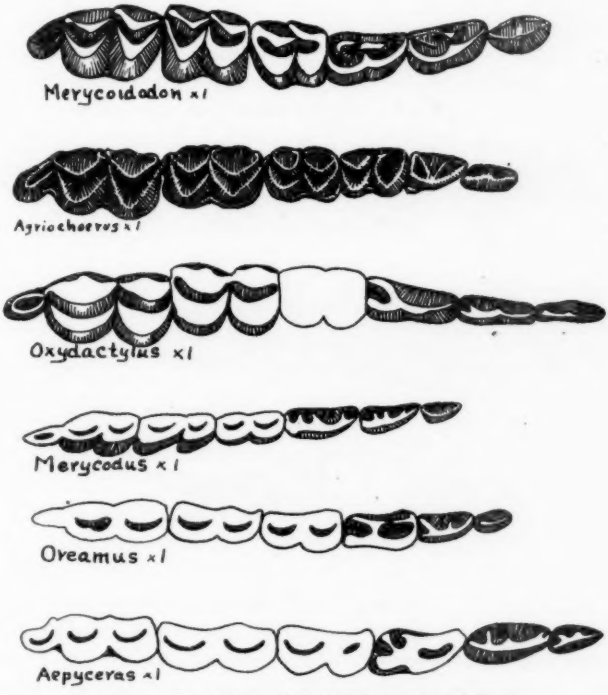

FIGURE 6.—*Comparison of typical lower dental Series*

Oreodonts are illustrated by Merycoidodon, agriochœrids by Agriochœrus, camels by Oxydactylus, deer by Merycodus, goats by Oreamus, and gazelles by Aepyceras.

that very little material belonging to the early history of bovidæ, gazelles, and antelopes has as yet been found.

For a study of the phylogeny of any one of these groups it is essential to have not only fairly complete dentitions, but also dentitions which have not been too much worn down. Neither too young nor too old animals show the typical and detailed characters.

The question arises at this point whether the variation within a phylum is such that it can be used to distinguish genera, and whether the subdivisions of a phylum have a like registration. In a complete survey of the oreodonts I found that the manner of forming the fourth upper premolar and the lower premolars was constant for the group, and also that changes from genus to genus were registered by minor variation and progressive modification of the premolars; and that these changes were correlated with body and foot structures. I have also noted that in the later genera of a phylum the more anterior premolars tend progressively to take on the characters of the fourth premolar. Where only the fourth premolar is modified, one is dealing with a less advanced genus. Where the third and fourth are modified, the genus is a later and more advanced

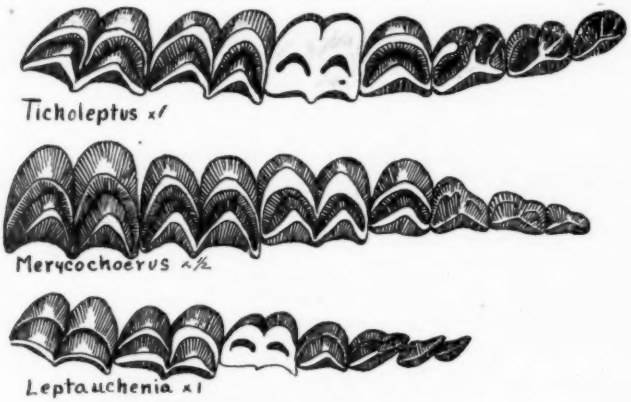

FIGURE 7.—*Upper Dentitions of Oreodonts*

type, and, lastly, where the second, third, and fourth premolars are all modified, the genera are advanced and specialized. Premolar 1 throughout tends to be reduced or lost entirely. Once a typical mode of modifying the premolars has been established, these characters progress forward from premolar 4.

SYSTEMATIC CONSIDERATION OF THE MAIN ARTIODACTYL PHYLA

It is not the purpose of this paper to work out the phylogeny of the various artiodactyl phyla, but I would like to point out those characters by which the major phyla differ from each other, and give enough details to illustrate the grade of variations which arise within a phylum.

The oreodonts (figure 7) are a singularly non-progressive group in the

structure of the limbs and feet, though they range from slender, agile types to heavy, sluggish forms. Ticholeptus is an intermediate type, Merycochœrus has a hippopotamus-like build, and Leptauchenia is one of the most slender and agile. Upper premolar 4 is uniform, but in the anterior premolars there is considerable variation in the amount of development of the crescents, especially the anterior one, in the presence or absence or development of the anterior intermediate crest and also the median crest.

The lower dentitions of oreodonts (figure 8) also show a common plan, but the anterior crescent may be weak or absent. The posterior crescent in Ticholeptus is small, in Merycochœrus large, and in Leptauchenia so swollen as to fill the posterior basin of the tooth. In the last mentioned

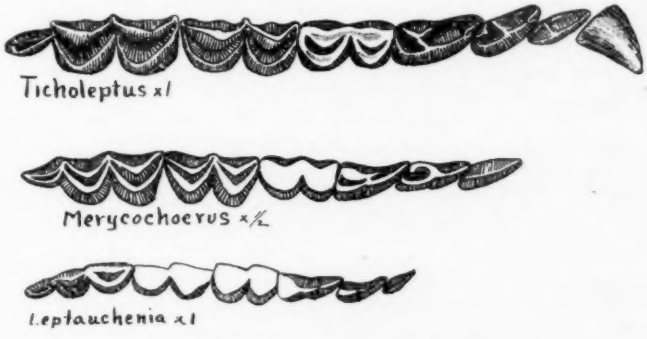

FIGURE 8.—*Lower Dentitions of Oreodonts*

genus one must take a very slightly worn tooth to see that the posterior crest and crescent are independent. These and similar differences run all through the phylum.

The Camelidæ (figure 9) are determined by the fact that in forming upper premolar 4 the tooth is foreshortened from front to back and the two crescents unite. The union is clearly visible in the earlier genera, though sometimes obscured in the later ones, but on favorable specimens it can often be detected even here. The generic characters of this group have been centered around the number of metapodials, the amount of their fusion, the elongation of the neck and limbs, and the loss of incisors and premolars. It is noticeable that in this group, instead of the character of premolar 4 progressing to the more anterior premolars, these teeth tend to be lost. The dentition of Protoceras clearly falls into this group, indicating how great may be the variation in other parts of the

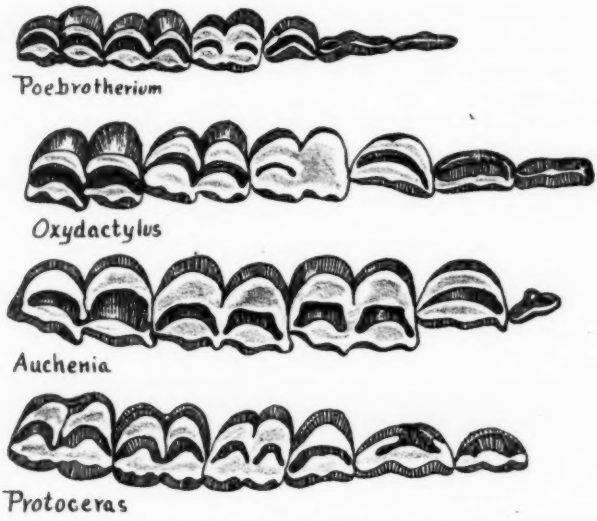

FIGURE 9.—*Upper Dentitions of Camels*
Natural size.

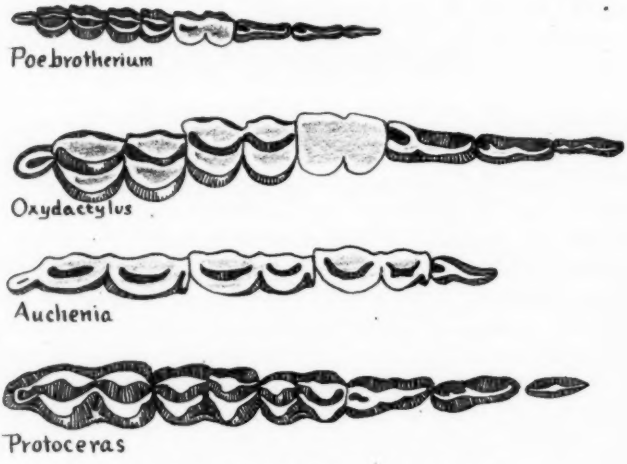

FIGURE 10.—*Lower Dentitions of Camels*
Natural size.

skull or skeleton without obscuring the fundamental characters as registered by the teeth, especially the premolars.

The lower dentition of camels (figure 10), as noted above, is characterized by their compression from side to side and the absence of crescents and all cross crests, except the posterior intermediate crest, which may end free behind or be joined to the posterior crest. The lower dentition of Protoceras is just as typically camel as is the upper.

The deer group (figure 11) immediately gives trouble, as the phylogeny has heretofore been worked out chiefly on the antlers, and it is surely polyphyletic. Without having made a full study of the group, I should say that Blastomeryx, Merycodus, and Cervus represent typical deer and successive stages of development. They have the upper fourth premolar formed by a foreshortening of the tooth from front to rear, but

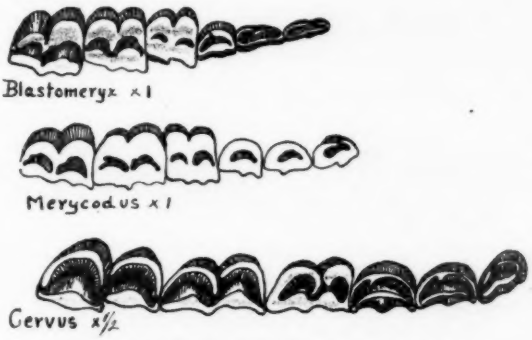

FIGURE 11.—*Upper Dentitions of typical Deer*

in the union of the crescents the anterior crescent overlaps the posterior one, which thus makes a spur projecting into the basin of the tooth. Blastomeryx is a Miocene form with only premolar 4 so modified; Merycodus is from the Upper Miocene and Pliocene and has both premolars 4 and 3 so modified, while the recent Cervus has all three of the premolars so foreshortened.

The lower premolars of deer (figure 12) are characterized by the marked development of the transverse crests, especially the posterior intermediate and the median crests, and to a less extent the anterior intermediate. In the latest of the series there is a development of the crescents not found in the earlier representatives.

In contrast to the above stand such deer (figure 13) as Mazama, Odocoileus, Alces, and Rangifer. They form the fourth upper premolar in a

manner similar to that of the deer proper, but the rear of each crescent, both anterior and posterior, is bifurcated. All of these are representatives of the advanced type, for all have the three premolars developed to the same degrees as premolar 4. There must be a fossil series back of

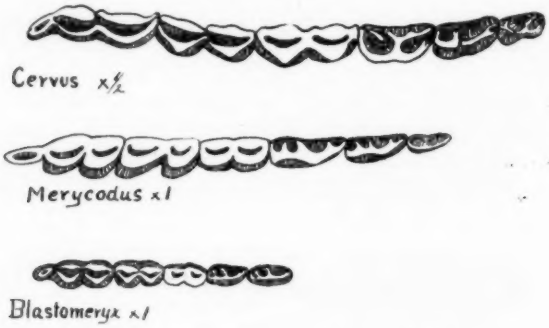

FIGURE 12.—*Lower Dentitions of typical Deer*

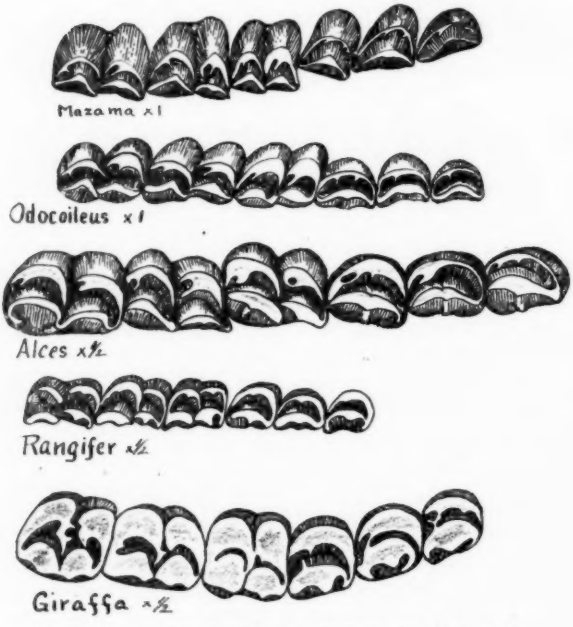

FIGURE 13.—*Upper Dentitions of Deer of the Alces Type*

these which is as yet quite unknown. I have placed a giraffe dentition with these, as some of the fossil representatives of the giraffes and sivatheres show a similar bifurcation of the rear of the crescents, and the lower dentition has the peculiarities of this group. The premolars of the giraffe are peculiar and differ from any type I have seen, though there may be intermediate forms to be found when the fossil series of premolars is studied.

The lower dentitions of the above genera (figure 14) are peculiar in that, on top of deerlike features of the cross crests, the posterior crescent

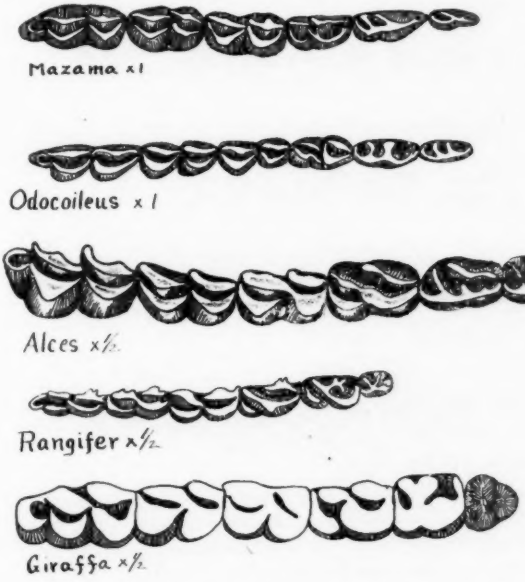

FIGURE 14.—*Lower Dentitions of Deer of the Alces Type*

of premolar 4 either is or tends to be united with the anterior crest. This leaves both the posterior crest and the anterior crescent more or less completely isolated. So far as I know, this condition is unique among artiodactyls and serves to separate this group from the deer on the one hand and unite them with the sivatheres and giraffes on the other. It unites such widely different forms as Mazama, which look like typical deer, and the giraffes, which have not been considered as close to the deer, though Sivatherium has been placed near Alces.

The hollow-horned artiodactyls are probably in considerable confusion. The goats, sheep, cattle, and gazelles have been in part sorted out, but the large group usually termed antelopes includes members of these phyla, beside at least one or more phyla which have not been worked out. Most of the known fossil forms are Pliocene and Pleistocene and their correlations are unsatisfactory. All are advanced types. Without doubt, some of the earlier forms now known as "deer" were hollow horned and belong in the antelope phylum or phyla.

The goats and sheep (figure 15) are characterized by the fourth upper premolar being formed from the anterior half of the tooth, the rear por-

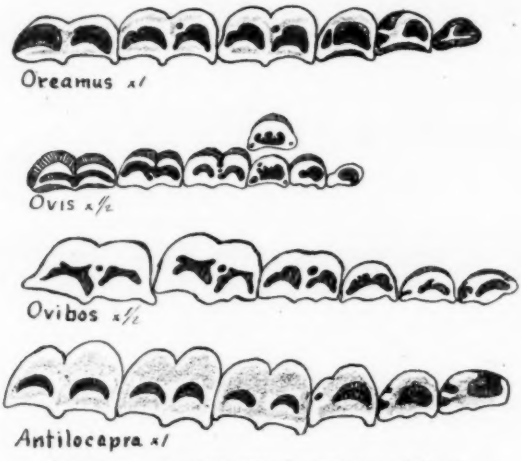

FIGURE 15.—*Upper Dentitions of Goats and Sheep*

tion being in varying stages of disappearance. Among the living goats this rear portion is retained as a small basin which is closed behind, though on premolar 3 this basin is still open. As far as dentition shows, the goats are not a highly specialized genus. Ovibos is much more advanced, having all three premolars modified to the form of the fourth. The sheep also are more specialized, and in them this rear basin is reduced to a small pit, only visible on teeth which are not much worn.

I have placed the Antilocapra dentition in this group, as it has the same type of premolar reduction, though there are peculiarities in it, the posterior basin being divided. There is still considerable comparative study to be done on this group before this association can be considered final.

The lower series (figure 16) show some relationship to the deer in the development of cross crescents, but it is to be noted that both the anterior

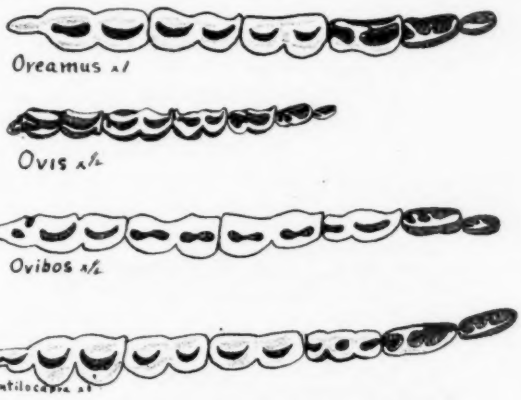

FIGURE 16.—*Lower Dentitions of Goats and Sheep*

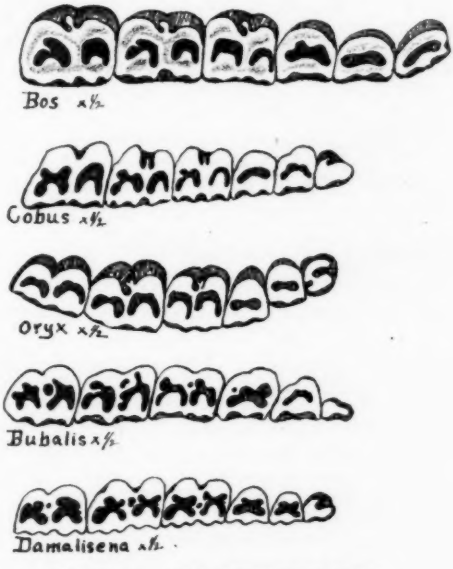

FIGURE 17.—*Upper Dentitions of Bovids*

and posterior crescents are well developed at the same time. While these transverse crests are strong on premolars 2 and 3, when the crescents are

strong, as on premolar 4, the transverse crests become reduced. In this group Antilocapra is differentiated by the posterior intermediate crest dividing the posterior basin into two parts, so that the tooth seems to consist of three parts.

The Bovidæ (figure 17) are somewhere near the sheep and goats, in that it is the anterior portion of the premolars which is preserved and the posterior lost. This loss is complete in *Bos taurus, B. indicus,* and some other species; but in such a species as *B. bison* traces of the rear portion are preserved. However, this group stands off from the goats and sheep by the excessive thickening of the cusps, especially the outer pair,

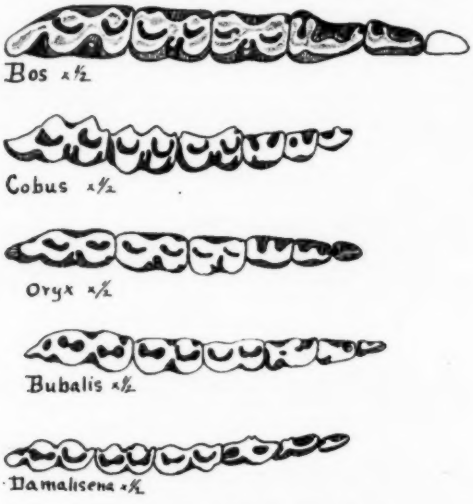

FIGURE 18.—*Lower Dentitions of Bovids*

so that they tend to fill the basins. Bos is further characterized by the development of a median style on the inner side of the upper molars and a corresponding one on the outer side of the lower molars. This is not of major phyletic importance, as it appears in some degree in many artiodactyls, but its considerable development serves to unite such forms as have it, along with other common characters. There are quite a number of "antelopes" showing the same peculiarities of bovid molar construction—that is, the thickened cusps and the styles—Hippotragus, Cobus, Boselaphus, Oryx, and Cervicapra, for example. Then there are a number which have the swollen cusps and premolar characters, but with-

out the style, such as Bubalis, Damalisena, and Connochætes. I believe all these belong to common stock and represent the divergences of later periods, as all the mentioned genera belong to the highly advanced types.

The lower dentitions of bovids (figure 18) show the same swollen cusps, especially in the molars and the median style, this time on the outer side. The cross crests are considerably developed, but peculiar in

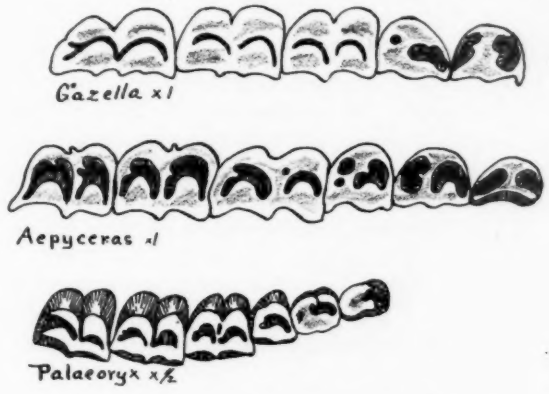

FIGURE 19.—*Upper Dentitions of Gazelles*

FIGURE 20.—*Lower Dentitions of Gazelles*

being swollen to a greater extent than in goats or deer. There is the same differentiation into two groups, those with the styles and those without, which I take to mean that there are two subphyla in this group. I have not cited all that belong to either group.

The gazelles (figure 19) illustrate the last method of forming the fourth upper premolar, where both anterior and posterior portions are

kept, but the two are divided by a strong median crest. Of the living forms the pala and the gazelles best illustrate it. There are a number of Pliocene and Pleistocene forms with lyrate or slightly curved horns, like Palæoryx and Protoryx, etcetera, in which the posterior basin generally seems filled, but in which little-worn specimens show it to be of the gazelle character. I feel that these belong to this group, and that the group is much larger than usually recognized.

The lower premolars (figure 20) of this group suggest deer in having the transverse crests well developed, but there is a tendency for them to meet on the inner ends and inclose small basins.

I have not attempted to fit into the above discussion the great bulk of both fossil and living forms, but rather to suggest the wide range of methods by which the premolars are formed among artiodactyls. It is rather a suggestion as to a new method of approach to the problem of the phylogeny of the group, which, taken with other features like the horns, antlers and feet, may make it possible to work out a phylogeny for this large and puzzling group. I do feel, however, that these methods of forming the teeth are deep seated, and will often make possible the correlation of forms which have diverged widely in external features.

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PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

MECHANICS OF CROCODILE VERTEBRÆ[1]

BY EDWARD L. TROXELL

(Read before the Paleontological Society December 30, 1924)

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INTRODUCTION

Since beginning the study of the fossil crocodiles, about two years ago,[2] one phase of that work in particular has challenged my attention, namely, that of the mechanical structure of the bones and its bearing on the life habits of these animals.

Some of the more striking characteristics of the vertebral column are here considered, and the advantages which may accrue to the crocodilian, as a result of them, are given first place in this discussion. These advantages may be a sufficient reason for the continued existence of the characters in question, but they do not, in themselves, explain the causes and origins; and, what is more, no attempt will be made to settle this question of derivation, which, I believe, no one fully understands. Most of the mechanical features which we have especially noted are such as to fit the crocodile to an aquatic existence and to the habits of a carnivorous animal.

[1] Manuscript received by the Secretary of the Society June 15, 1925.
[2] In part a contribution from the Marsh Publication Fund of Peabody Museum, Yale University.

Mechanical Features

Size of vertebræ

A prominent feature, but one of only moderate interest, is the decrease in size of the vertebræ in both directions from the pelvis. Someone may say at once that this is due to the fact that the hind legs bear the greater part of the weight of the walking[3] animal, and this is, no doubt, in part true; but, in addition, the structure is of advantage to the swimming animal, in which the tail is the propelling organ.

Each vertebra of the tail, therefore, transmits the thrust of that portion of the tail which lies behind it; and, as this force increases forward, it is of advantage to have the vertebræ increasingly greater in size. Similarly, but in opposition, the body of the animal in front of the pelvis furnishes the resistance to progression through the water, and the force of this resistance is cumulative from the head backward, so that each succeeding vertebra receives the sum total of all the resisting force of all the vertebræ in front of it.

Procœlous vertebræ

Just why the vertebræ of the crocodiles (and most living reptiles) are procœlous is a question which can not be answered here, except in a most general way, by ascribing it to "natural selection," "orthogenesis," or some other causative factor; nevertheless, the benefits which came as a result of this, from the standpoint of mechanics, are various and evident. In all the true crocodilians the vertebræ are procœlous—that is, they are concavo-convex and the hollow end is in front. A ball-and-socket joint such as this, it is easy to see, furnishes an intimate contact of the joint-surface over a greater area, continuously, and lends itself to a universal movement through wide angles. Throughout the movement one segment glides with ease on the other; there is, therefore, great pliability in the tail and body of the crocodile, which swims vigorously and uses its tail strenuously[4] for short periods of time.

Two advantages come from having the anterior concavity and the posterior head on each of these vertebræ: (*a*) the protection of the cup, the weaker structure, and (*b*) greater action for the amount of angular movement.

Considerable importance (*a*) is attached to the fact that the thrust for-

[3] One eminent authority contends that the crocodiles come from a bipedal ancestry!

[4] Bedard tells of the crocodile striking its prey with a side sweep of its tail, and Ditmars relates how he, himself, was knocked headlong by a blow delivered in this manner.

ward through each vertebra is in the direction of the longer axis of that vertebra, and therefore is normal (perpendicular) to the surface of its cup at the central point (see figure 1, A). On the other hand, the thrust on the vertebra in front may be in an oblique direction against its posterior convex surface, the solid ball, but it is massive and capable of withstanding the stress. Reversing[5] the conditions (figure 1, *b*), we see that if the thrust comes from the ball, meeting the cup in an oblique angle, there would be a tendency to shear off the rim of the cup. It must be clearly understood that the thrust through each vertebra is transmitted (lateral muscular pull not considered) in the direction and along the line of the longer axis to the next vertebra in front.

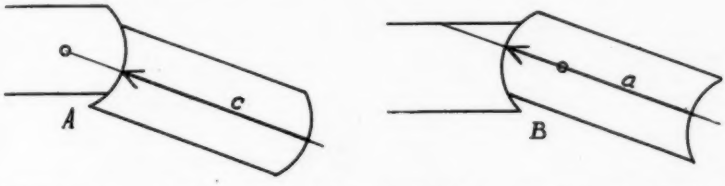

FIGURE 1.—*Diagrams showing Contrast in the Action of procœlous (A) and postcœlous (B) caudal Vertebræ when the Tail is used in swimming*

A. With the hollow end forward, the actual condition in the crocodile, the axis of force passes through the center of the cup and is directed on the solid head at an angle. Compare figure 2, *c*.

B. In the postcœlous type of vertebræ the force would be against the rim of the cup, a weak structure. For any degree of angular motion, the vertebra is not displaced so far to the side. Compare figure 2, *a*.

With reference to the greater action (*b*) per unit of angular movement, we see that in the case of any "ball-and-socket" joint the *center of movement*—and it is a center rather than an axis—is within the ball. In the procœlous vertebræ this center is thrown forward a distance even greater than the radius of the ball itself. The lateral movement of a vertebra, therefore, depends not on its actual length, but on its functional length, as measured from its center of movement (see figure 2, *x, y, z*).

Three conditions are considered in figure 2: (1) When the center of movement is on the surface of contact—hypothetical; (2) when the center of movement might be in the posterior vertebra—supposedly postcœlous; and (3) the center of movement forward, as in the procœlous vertebræ of *Crocodilus*.

In the first case the line *b* represents the center line or longitudinal axis of the supposed case of a vertebra swinging on the point *y;* for the

[5] It is conceivable that in articulating a lot of loose vertebræ an inexperienced person might turn each vertebra end for end and build a weaker structure.

same degree of angular displacement the amount of actual movement is moderate. Similarly, the line *a* (in hypothesis or in a condition reversed from A, figure 1, the true case), the axis of a vertebra with an anterior *convex* surface, rotating about the center *z*, gives much less sideward movement to the vertebra.

In the third case, similar to the condition shown in figure 1, *a*, the letter *c* marks the axis of a vertebra which has moved to one side about the point *x*; the whole line *c* represents the functional length of the vertebra in the procœlous state.

In the three cases the amount of water displaced by the swimming movement of the tail would be represented by the triangles whose bases are *a*, *b*, and *c*, respectively. These triangles are to each other as the squares of the lines *a*, *b*, and *c*, which are in turn the functional lengths of the vertebræ represented.

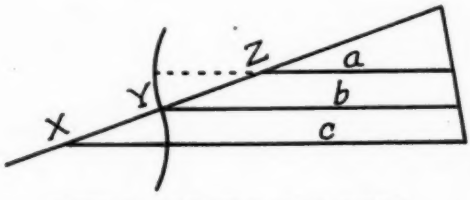

FIGURE 2.—*Longitudinal Axis of Vertebræ*

The lines *a*, *b*, and *c* represent the longitudinal axis of vertebræ which are in turn postcœlous, amphiplatyan, and procœlous; the first two are hypothetical cases. The lines also express the functional lengths of the vertebræ when they rotate on the points *z*, *y*, and *x*.

For the same angular movement, therefore, it is evident that in *c* there is the greatest lateral displacement; the areal displacement and the volume of water moved in swimming, moreover, varies as the squares of *a*, *b*, and *c*.

Therefore, the water displaced as the result of the movement of any one vertebra varies as the square of its functional length (see figure 2), and this factor in *one vertebra* affects the tail throughout its length posterior to that vertebra, but does not, however, give a progressive increase—an increment—from joint to joint. Take, for example, the diagrammatic representation in B, figure 3, where the first segment alone is procœlous, with the rest platycœlous; this gives the effect of moving the tail to one side an amount corresponding to the lateral displacement of the first segment only.

There is, however, a progressive increase in the displacement of the tail where all the vertebræ are procœlous in their action and effect. In the diagram, figure 3, broken line C, each vertebra has an increased func-

tional length and each has an additional sideward movement, as a result. The effect is, therefore, cumulative in the series and, in view of the fact that there are many caudals, the results are notable. The operation produces a forward and backward motion in the tail (when it curves and straightens) in amount dependent upon the translocation of the center of motion, or the difference between the actual length and the functional

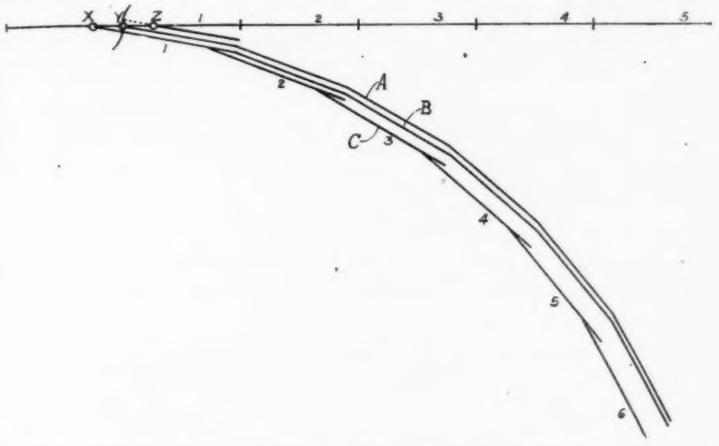

FIGURE 3.—*Diagram representing three possible Conditions in the Tail of the Crocodilian depending on the Nature of the Vertebræ and the Positions of the Centers of Movement*

The broken line marked A shows the segments of the tail bending or moving about centers on their contact surfaces (see point Y and see also *b* and Y, figure 2). The movement, through an angle of 10 degrees in each case, would be the approximate condition found in amphiplatyan vertebræ; compare *Hyposaurus*, a Cretaceous crocodiloid.

The line B represents a case where the first vertebra only might be procœlous, and it alone has the increased functional length, measuring from the point X. The other joints are similar to those of line A, but have a greater lateral translation brought about by segment number 1.

The line marked C gives the actual condition in the modern crocodile and alligator, disregarding for the moment the doubly convex first caudal. In each segment the center of movement is thrown forward, causing the tail as a whole to be moved forward with an added increment from vertebra to vertebra.

The action here described is, of course, that near the base of the tail; the distal segments are smaller and less perfectly formed.

length of a vertebra. Probably this is the most important element in the whole principle of the procœlous vertebræ, because the backward movement of the tail causes the drive which sends the body forward.

THE FIRST CAUDAL

The first segment of the tail of the crocodilian is doubly convex; it is almost unique among animals in this respect. This peculiar bone, al-

though it reverses some of the principles already ascribed to the other crocodilian vertebræ, has certain definite mechanical advantages.

As already stated, in a ball-and-socket joint the center of motion is a point within the ball; in this doubly convex segment, then, there are two

FIGURE 4.—*Alligator Sacrum, rear, and first Caudal, side and bottom views*

These illustrations were drawn from specimen number 576, in Peabody Museum. The posterior end of the sacral centrum is concave. The first caudal shows the doubly convex ends. Note on the bottom view the two dots, which mark the centers of movement about which the adjoining vertebræ rotate.

centers and it is, moreover, much shortened functionally. The anterior ball is broad and has a longer radius of curvature than has the posterior head; its center of motion is within four millimeters of the midpoint of the centrum itself.

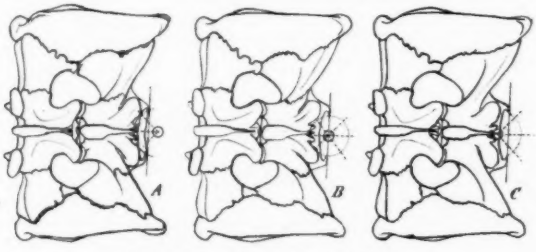

FIGURE 5.—*The Alligator Sacrum*

A shows the actual condition existing in all crocodilians; B and C are hypothetical cases. In A the dotted line represents the normal cup, with the center of movement outside of the sacral itself. A deep cup or prominent ball would place the center of movement on the straight line (B). As shown in C, a low convex articular surface would throw the center of movement forward into the sacral centrum.

The advantages derived are these:

1. It gives the sacrum greater functional length without decreasing its strength.

2. It permits a shorter sacrum without congesting the movements at the base of the tail.

3. It makes a stronger, more solid block of the first caudal.

4. It gives the first caudal the effect of an extremely short joint, yet retains the conveniently long centrum.

Nature has reversed the form of the anterior end of this first caudal from the ruling procœlous type, with the result that the center of motion is thrown backward and away from the sacrum. This is a striking example of the modification—in this case the reversal—of a structure in order to gain certain ends. The concavo-convex vertebræ of the tail in

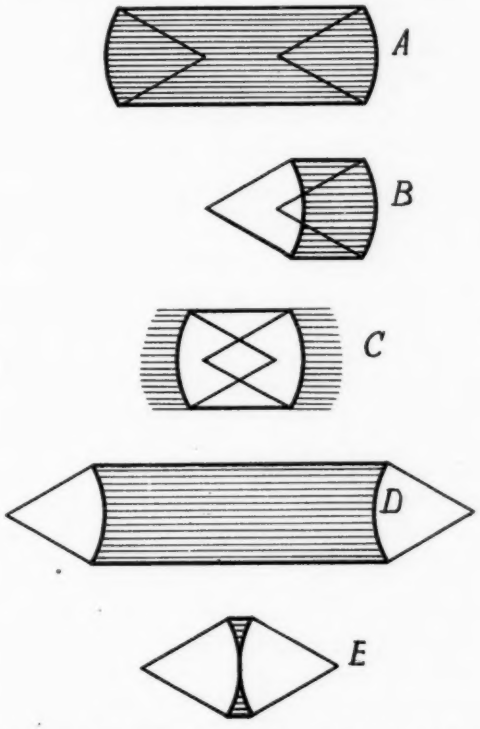

FIGURE 6.—*Mathematical and diagrammatic Representations of the first Caudal in the actual Form, A, and under hypothetical Conditions, B, C, etcetera*

The straight oblique lines are the radii; the curvature is the same in each case.

general have a definite function; but, passing from the region in which they operate, we find the first caudal so specialized in its construction as to give a totally different result. Certain possible variations in the form of the first caudal are shown in figure 6, and the table gives the change in functional length in each instance.

Form of caudal, actual or conjectural	Length of caudal	
	Measured Millimeters	Functional Millimeters
A true specimen.		
(A) Doubly convex	45	12
Hypothetical cases.		
(B) Concavo-convex, same functional length as A	12	12
(C) Doubly concave. A vertebra of negative length (imaginary) with the functional length as in A and B	21	12
(D) Doubly concave. Same measured length as in A, functional length greatly increased	45	78
(E) Doubly concave. With length of zero, such a vertebra would have a functional length of 21 millimeters	0	21

ZYGAPOPHYSES AND THEIR MEANING

The post- and prezygapophyses of a vertebra are projections which extend in pairs forward and backward, respectively, from the neural arch. The one pair comes in contact with the other and is movably articulated.

The prezygapophyses of the crocodilian caudal vertebræ have their articular surfaces facing upward, inward, and slightly forward; the faces of the postzygapophyses are directed downward, outward, and backward. The effect which this produces, as the postzygapophyses slide under the opposing surfaces alternately, is to cause the vertebræ to tip to one side and the other, in their otherwise simple lateral movement, producing a moderate rocking motion of the tail in its sideward swing. I have seen in the living alligator this slight swaying, and it seems to have its use in giving the dorsal row of horny plates greater effectiveness in catching the water. In a negative way these apophyses prevent a twisting in the opposite direction, as a result of the contact of the horny dorsal plates of the tail with the water; this is perhaps their most important function.

NEURAL SPINES AND CHEVRONS

Certain structures of the caudal vertebræ have an important part to play in a peculiar feeding habit of the crocodile and alligator; these are the shafts of bone which project upward and downward from the vertebræ—the neural spines and chevrons.

The chevron bones are usually thought to be for the protection of blood vessels which thread the hæmal arch. That they do this is undoubted, but where we find them in the form of a letter Y, with a greatly elongated,

rugosely terminated, and enlarged stem, we think of them as performing a function similar to that of the neural spines, namely, as trusses and levers for the ligaments and muscles, intended not only to support, but to aid in bending[6] the tail in the vertical plane.

It is known through actual observation that the alligator can bend its tail upward and downward and of course sidewise and in any intermediate direction. It is therefore capable of swinging the tail around in a wide circle, which it will do if held, by the pelvic region or the base of the tail, suspended, head downward.

The crocodilian makes a remarkable use of its ability to do this. It can lie flat on the ground, form the arc of a circle with its body length, and roll over and over in one place. It does this by the identical action described above. However, the weight keeps the body and tail flat on the ground, and therefore transforms the swinging movement of the tail into a rotation of the whole body.

That the limbs play no part in this process is easily seen. The arms are held tightly against the side, while the hind legs project backward and are limp.

It is said that two animals will seize the same object, presumably a piece of meat, and, turning in opposite directions, rend it asunder. The stimulus of a twist in one direction seems to spur an alligator to revolve in the other; it is not difficult to induce the action in a captive animal through this means.

PROBLEMATICAL FEATURES

There are certain structures in the crocodile skeleton whose meanings are not entirely clear. One of these is the hypapophyses which characterize all crocodiles and, indeed, give the generic name to the Cretaceous form, *Hyposaurus* Owen.

The hypapophyses are processes which extend ventrally from the anterior dorsal and posterior cervical vertebræ. They must surely be for the attachment of muscles and ligaments, and, if so, it is probable that they aid in bending the backbone, or, in other words, of pulling the head downward; and they may aid, through their ability to curve the body, the remarkable method of securing food already described.

[6] We have observed that in *Megatherium*, the giant sloth, there are chevron bones, which, it is presumed, aided in holding the tail as a rigid and partial support for the heavy body, as the animal reared on its hind legs to feed. Chevrons are found also in Cetaceans and Sirenians, where aquatic locomotion is brought about by the movement, upward and downward, of a horizontally flattened tail.

Summary and Conclusions

All the points here noted have revealed advantageous features. Although at times there seem to be minor disadvantages, this is inevitable in so complex a machine as a vertebrate skeleton.

No one would hesitate to say that the teeth were of advantage in securing food, nor to state that the limbs are for locomotion. There is equally good reason for ascribing to minor features of the vertebræ, though less well known, the benefits which they give an animal.

We have discussed the relative size of the vertebræ, the processes which grow out from the centrum, including the chevron bones, and we have considered the meaning of the terminations of the centra—whether doubly convex, concavo-convex, or having flat ends. Nearly all these features have a bearing on the aquatic life or on the methods of securing and devouring the prey; they are delicate adjustments or ingenious devices which bring the machine as a whole up to a higher stage of efficiency.

Thus we see how from the bones we may draw inferences as to the life activities and environment in which an animal lives. Furthermore, a fossil skeleton—a diagram of a once living being—gives us a clue to the interpretation of the habitat and habits of ancient forms and makes their inanimate bones live again.

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MINERALIZATION OF THE PLATTEVILLE–DECORAH CONTACT ZONE IN THE TWIN CITY REGION[1]

BY CLINTON R. STAUFFER

(*Presented in abstract before the Society December 31, 1924*)

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INTRODUCTION

The middle Ordovician of the Twin City (Minneapolis–Saint Paul) region forms an isolated patch of outcrops. It is an outlier from the great area to the south and east which is covered by these formations and to which it was definitely united until very recent (probably late Tertiary) time. The characteristics of these formations, as observed in this outlier, are much the same as in the more extensive area. However, in both regions these formations differ somewhat in composition from place to place, and with this dissimilarity there is a corresponding variation in the chemical changes that have taken place since the deposition of the sediments. Recently rather extensive excavations and tunnelings have been made in the Minneapolis and Saint Paul area, which show especially the basal Decorah shale, all of the Platteville limestone, and the upper

[1] Manuscript received by the Secretary of the Society December 31, 1924.

part of the St. Peter sandstone. Since these cuts are in the fresh rock, quite removed from the outcrop and protected either by argillaceous beds of the Decorah shale or the compact boulder clays of the Kansan drift, they have afforded an unusual opportunity to study the unaltered Platteville–Decorah contact and the beds just below it. This constitutes a zone in which rather extensive mineralization has taken place and in which the order of these changes can be followed with a fair degree of certainty.

Characteristics of Horizons affected

Generalized section

The following is a generalized section showing the relationship of the beds under discussion and is approximately that exposed during the construction of the new Ford automobile factory in Saint Paul:

	Thickness	
	Feet	Inches
Decorah shale:		
9. Shale, argillaceous, soft, blue, alternating with occasional layers and lenses of blue limestone	30±	
8. Limestone, gray to bluish	2	0
7. Shale, soft, gray to bluish white	0	3
6. Limestone, dolomitic, hard, coarse, rough, brown in color	1	6
Platteville limestone:		
5. Limestone, dolomitic, gray to bluish	8	0
4. Limestone, dolomitic, shaly, blue in color	6	0
3. Limestone, compact, hard, blue in color and with irregular shaly partings	12	0
2. Shale, bluish, somewhat calcareous and often sandy	3	0
St. Peter sandstone:		
1. Sandstone, white, poorly cemented	70±	

The Platteville limestone

Exclusive of the shaly base (bed 2), usually regarded as transitional from the St. Peter sandstone, but probably a part of the succeeding formation, the Platteville is made up of three rather distinct divisions. These have no sure relation to the faunal content, but are dependent on the physical character of the sediments composing them and on their present chemical composition.

The lowest of these divisions (bed 3) consists of about 12 feet of compact, hard, blue limestone with numerous thin streaks of blue shale. The limestone layers are irregular and more or less nodular, yet continuous, and the thin shaly partings are an intimate part of the limestone; so that the whole separates into more or less massive beds at still more

prominent partings. This is the building stone of the Twin City region and was formerly used on a rather large scale for such purposes. It contains some fossils, which at certain places are quite abundant. Essentially all of them preserve the shell, occasionally with even the mother-of-pearl luster. This portion of the formation has been changed but little, if at all, from its original composition as a calcareous mud on the bottom of the Ordovician sea. Numerous chemical analyses[2] show it to run about 80 per cent $CaCO_3$, with only about 5 per cent $MgCO_3$. Most of the remainder is clay.

The middle portion (bed 4) of the Platteville consists of about six feet of rather massive argillaceous dolomitic blue limestone which is often in part a true shale. It is quite compact and rarely fossiliferous, except in occasional pockets or patches where fossils may be common. Often these fossils are more or less broken up, as if they had been drifted together, but they are now preserved chiefly as molds. Analyses show this rock to contain about 26 per cent $MgCO_3$ and 46 per cent $CaCO_3$; the remainder is argillaceous material. The rock thus approaches a real dolomite, although rather high in impurities.

The upper 8 feet (bed 5) of the formation is a gray to bluish gray dolomitic limestone with little or no shale. These beds are often highly fossiliferous, and in places such remains are matted together like modern shells in the coquina of Florida. Except for the trilobites and lingulas, which still retain their original shells, these fossils are preserved as molds still more or less open and not deformed. Before the mineralizing changes, therefore, they were not only preserved as the original shell, but must have been almost undisturbed in the place where they fell when the animals died. Undoubtedly, therefore, when deposited this part of the formation was highly calcareous. At present, however, it is the most dolomitic part of the Platteville, having about 30 per cent $MgCO_3$ and only about 46 per cent $CaCO_3$. This is approaching the composition of the dolomitic limestones of the Oneota (Lower Magnesian Series) and is even lower than the Oneota in its percentage of $CaCO_3$.

THE PLATTEVILLE-DECORAH CONTACT

Although the Platteville-Decorah dividing line throughout the State and in adjacent territory, as based on the fauna, is somewhat unsatisfactory, the most convenient separating surface here, in the Twin City region, makes an exceedingly sharp line of contact.[3] The top of the

[2] The analyses for this paper were made by R. J. Leonard.
[3] F. W. Sardeson: Am. Geol., vol. 22, 1898, p. 318.

Platteville is slightly uneven and often somewhat pitted. Over this, and gradually disappearing downward through several inches or more, is a black stain caused by finely divided pyrite with a trace of manganese. At the top this stain is so concentrated that it forms a crustlike covering for the rock. Where this covering is well preserved the overlying Decorah separates readily from the Platteville; but where it was apparently broken through, when the later sediments were laid down, the Decorah is tightly welded to the Platteville, but still shows the dark band at the contact.

Loose pieces of the Platteville incorporated in the basal bed of the Decorah are not abundant, but those found are also coated with the black stain, just as if they had lain upon the Platteville surface during the time it was receiving the coating. In a few instances the pyrite crust has been broken up and slightly mingled with the oncoming brown sediments of the basal Decorah. In such cases there may be formed a secondary, but less pronounced, band of blackened rock a few inches above the main one, but it is never so important, nor is there an upward permeation of this stain corresponding to the downward penetration above described.

As a break in sedimentation, this contact is not wholly unlike others that have occurred throughout the Ordovician or even far back into the Cambrian of Minnesota. Some of these occur within formations and may have irregular surfaces associated with pebbles, but they have not developed the crusted surface and the accompanying pyrite stain to anything like the perfection which it has attained at the top of the Platteville, nor is there the same evidence of the lapse of time, except at the well established contacts of formations. It seems safe to conclude, therefore, that the top of the Platteville, as here described, not only represents a break in sedimentation, but probably a real disconformity.

THE BASAL DECORAH SHALE

There is a marked change in the character of sediment from the fine-grained, rather dense, gray dolomitic rock of the Platteville to the hard, coarse, rough, brown dolomitic limestone of the basal Decorah (bed 6). Most of the limestone layers occurring at intervals in the Decorah shale are highly calcareous, and the contained fossils, except the Mollusca, are usually preserved with the original shells; but the basal layer, 18 inches thick, is nearly 14 per cent $MgCO_3$ and about 54 per cent $CaCO_3$, the latter substance being 8 per cent higher than in the upper layers of the Platteville. Its fossils, except the lingulas, are mere holes in the rock, which evidently represent poorly preserved molds.

Just above the basal layer of the Decorah occurs an inch and a half

to three inches of soft, pale blue to gray or white, tough, sticky clay shale,[4] which is almost impervious to water. While this thin bed in itself may not have been sufficient to prevent the upward movement of the mineralizing solutions, it was reinforced by the thick clay shales above, so that the mineral changes at higher horizons in this locality are practically negligible and have no definite relation to those below. It is thus evident that the upper limit of the zone of marked mineralization is rather definitely drawn by the thin bed of shale near the base of the Decorah, and that the lower limit is equally determined by the argillaceous shaly beds of the middle Platteville.

Mineralization

Crusted surface of the Platteville

The formation of the blackened upper surface of the Platteville seems to constitute an event quite independent of the other mineral changes that have affected this zone. The finely divided condition of the pyrite, which causes the stain, together with the fact that it is chiefly confined to the contact and does not penetrate the overlying rock, although it does coat fragments of the Platteville incorporated in the Decorah, leads one to suspect that it antedates the latter in deposition, and that it may have been precipitated by bacterial action during a time when no other deposition was taking place.

In the salty lagoons bordering the Black Sea, Andrussow[5] found a finely divided iron sulphide being deposited partly in the mud and partly as a coating on other substances. This is being precipitated by different types of bacteria and forms a deposit suggestive of the top of the Platteville. At least two of the bacteria, *Vibrio hydrosulfurous* and *Bacterium hydrosulfureum*, separated from the Black Sea mud,[6] are sulphate reducers and in the process liberate hydrogen sulphide in quantity. This will attack the iron present in the sea water, producing a sulphide, or the iron sulphides may be formed directly through the iron bacteria, thus giving rise to black mud; but the interesting point here is that the very presence of hydrogen sulphide, and therefore of the bacteria themselves, would foul the sea bottom and render it unfit for the abundant development of the Brachiopoda and Mollusca which were so characteristic of the

[4] F. W. Sardeson calls this bentonite. Pan-Am. Geol., vol. 42, 1924, pp. 47-48.

[5] N. Andrussow: La Mer Noir. Cong. Geol. Internat., Guide des exc., 7° Sess., Exc. 29, 1897. p. 7.

[6] W. Omelianski: Der Kreislauf des Schwefels, in Franz Lafar's Handbuch der technischen Mykologie, Band 3, Auflage 2. Jena, 1904-5, pp. 214-220.

life of Platteville time. This would help to bring about the break in sedimentation here observed and may have been its chief cause, at the same time that the sulphide crust and its accompanying stain were formed.

SOLUTION

From the present condition of the fossils preserved in the upper part of the Platteville and the basal Decorah, it appears that the first mineral change taking place was that of solution or the removal of large quantities of calcium carbonate. This affected especially the more soluble shells, which occurred in abundance in the upper Platteville, but left unaffected those of phosphatic composition, such as the trilobites. Apparently the water responsible for this change in the Twin City region was unable to penetrate appreciably the lower part of the Platteville or the overlying Decorah, in both of which shaly beds occur, for in the lower beds all fossils retain the shell, while in the upper beds all but the Mollusca retain the shell.

DOLOMITIZATION

The next change was dolomitization, during which a little more than one-third of the calcium was replaced by magnesium. This caused a certain amount of shrinkage, which rendered the rock slightly porous, but the fossils were not destroyed. In the Oneota, or lowest Ordovician, where this process has gone only a little farther, fossils are exceedingly rare, except in the cherty layers of certain localities, where they are replaced by silica, and in which layers the number of fossils suggests their probable abundance in that formation as a whole when it was a limestone high in calcium carbonate.

If the destruction of fossils is due to the process of dolomitization, it would seem that the introduction of only a little more magnesium might have been sufficient to remove most, if not all, traces of life from the upper part of the Platteville. The fact that they are still so well preserved is regarded as an indication that a certain amount of solution had preceded dolomitization, and that when the latter process took place there was no mineral matter in these cavities that could be affected by it. The rock thus became porous, but the molds retained their shape. These two processes are always somewhat related, as dolomitization necessarily means the removal of calcium, but by a process of substitution of magnesium for half of the calcium in $2CaCO_3$, resulting in the formation of $CaMg(CO_3)_2$.[7] In the case under consideration, however, the shells of

[7] C. R. Van Hise: U. S. Geol. Surv. Mono. 47, 1904, p. 798.
Also F. W. Clarke: U. S. Geol. Surv. Bull. 695, 1920, p. 557.

the fossils have not been dolomitized, but entirely removed, which in itself seems to indicate that they were carried away in solution before the magnesium-bearing waters entered the rock.

PYRITE DEPOSITION

After the shells had been removed by solution, iron-sulphide-bearing waters entered the same zone and a thin, continuous coating of pyrite was deposited as a lining over the inside of most of the molds, partially filling nearly all other openings. Some of the cracks and joints were thus converted into miniature veins, while some parts of the rock, especially the basal layer of the Decorah, are highly impregnated with it. Pyrite and marcasite are common constituents of the Ordovician rocks of this region, but it is rarely that the order of their deposition can be so definitely fixed as in this case. As pointed out above, it is certain that part of the iron was introduced at an early date, but the greater part of that now occurring in the upper Platteville and basal Decorah was brought in after solution and dolomitization. This is shown by its relation to the fossil molds. In many places the pyrite is finely crystalline, showing well developed cubes, many of which are twinned. Small quantities of sphalerite and even galena may occasionally be found, and their relation to the iron sulphide suggests that they may have been introduced with the pyrite.

CALCITE DEPOSITION

After the period of pyrite deposition, solutions charged with calcium bicarbonate entered this zone, and the cavities that were earlier lined with pyrite received a coating of calcite which developed a variety of crystal forms. Many of the cavities were completely filled, while others remained as irregular geodes. The smaller of these may be separated from the limestone as nodules of pyrite, which, when broken open, prove to be filled with masses of calcite crystals. In the matted masses of fossils, referred to as characteristic of parts of the upper beds belonging to the Platteville, the surfaces of the molds sparkle with the innumerable calcite crystal faces, and the identification of the species is thus often rendered difficult. Some calcite occupying pore spaces within the rock itself was apparently introduced at this time, but this is not quite so obvious. However, a complete reversal of the type of solutions passing through the rock had taken place. Instead of the dissolving or substituting liquids, the waters were charged with calcium carbonate ready for deposition. The calcite crystals then formed are quite pure, running as high as 98.69 per cent $CaCO_3$. The order of mineral change taking place has thus con-

formed to that of the mineralized region of Wisconsin[8] and other similar areas.

The changes now taking place at the outcrop of this horizon are chiefly leaching of the carbonate and disintegration of the pyrite. The mineralization here presented is thus soon obliterated, and there is left at such places no adequate record of the sequence of events that have taken place.

Summary

Exclusive of the pyrite crust at the top of the Platteville, it appears that the Platteville-Decorah contact zone has passed through four successive stages of mineral changes. The first of these was solution affecting chiefly the highly calcareous shells. Then followed dolomitization, during which magnesium was substituted for part of the remaining calcium. Iron-bearing solutions next deposited pyrite in the pore spaces, cracks, and cavities. Later the pyrite coatings were covered by calcite, which either filled the cavities or converted them into geodes.

[8] U. S. Grant: Wis. Geol. and Nat. Hist. Survey, Bull. 14, 1906, p. 74.

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KEYSTONE FAULTS[1]

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DEFINITION

Master joints converging downward and bounding V-shaped blocks or wedges of rock of more or less acute angle and varying magnitude may be momentarily opened by tensile stress during the passage of earthquake vibrations. When this happens the unsupported or imperfectly supported V or keystone promptly drops, as into a vise, and is more or less extensively broken and crushed, at least in the upper part, by the powerful

[1] Manuscript received by the Secretary of the Society February 16, 1925.

compressive stress of the succeeding phase of the earth vibration. This dual action, or alternation of tension and compression, simulating the operation of a jaw crusher, may be repeated many times during the passage of an earthquake, the depressed block, or keystone, tending to sink deeper with each successive pulsation; and the narrow graben, or trough fault, thus resulting is, in its simplest terms, the keystone fault. The advisability of the distinctive name will, it is believed, become apparent as the examples are described and discussed; but first we may enlarge somewhat upon the definition.

We need not, of course, insist upon a common origin for the master joints, nor that they everywhere—nor anywhere, for that matter—antedate all other types of jointing; also, it is plain that the possible development of keystone faults is not limited to the master joints, although it is probable that they furnish the more ideal and impressive examples. Again, in the cracking and crushing of the keystone we have at least a partial explanation of the vastly irregular secondary jointing and the fact that the individual secondary joint is rarely traceable across a master joint.

With master joints converging downward, the keystone ends, of course, where the joints meet, in the thin edge of the wedge. Below this level no faulting need be postulated; but we should expect, instead, a fissure more or less open, according to the degree of resistance to crushing which the keystone offered and the nature of the rock. The substitution of hydrostatic pressure for rock pressure, which an open fissure implies, is a fact of the first importance, especially in its bearing upon the deposition of dissolved minerals and the formation of mineral veins and ore deposits.

As the keystone fault terminates downward, or subterraneously, by the convergence of its walls, so, also, it may terminate horizontally by convergence of its walls, the keystone tapering either or both ways to an edge; or it may end either or both ways, abruptly against a master joint. In the local shaking down of its potential keystones we have, apparently, an adequate explanation of the compressive stress known to exist in many parts of the earth's crust, and of which we have striking examples in quarries of granite and other stones.

In not a few instances the development of the keystone faults clearly belongs to postglacial time. In fact, it is here that we find the truly impressive and convincing examples of postglacial faulting, and not in the minute dislocations, rarely measuring more than a small fraction of a foot in throw, described in recent years and occurring mainly in finely jointed slaty rocks. For these miniature faults, of convenient illustra-

tive magnitude, frost action would seem to furnish, in many cases at lease, a rational explanation.

The question is certain to be raised as to the distinction of keystones and grabens, and it might well seem that they are essentially similar types of structure, as minor and major examples of linear block or trough faulting. On second thought, however, it appears that the distinction is more than one of relative magnitude; more, too, than difference in form would imply, the contrast being essentially causal or dynamic. Our best suggestion, therefore, is that if two master or major joints of parallel strike and convergent dip are so near together as to be opened simultaneously by the passage of an earthquake tremor, the included block or keystone will drop uniformly, yielding two normal faults of approximately equal throw and opposite hade. But if the limiting master joints are so widely spaced as to be affected successively and not simultaneously by the earth vibrations, first one side of the block will drop and then the other; and a typical block fault, or graben, and not a keystone, is the result.

Viewed in this light, the Rhine Valley between the Black Forest and the Vosges Mountains, the East African Great Rift Valley, the Triassic troughs of the Atlantic seaboard of North America, and scores of examples that might be cited are readily recognized as typical grabens, requiring radically different classification than the Sutton "Purgatory," now to be described.

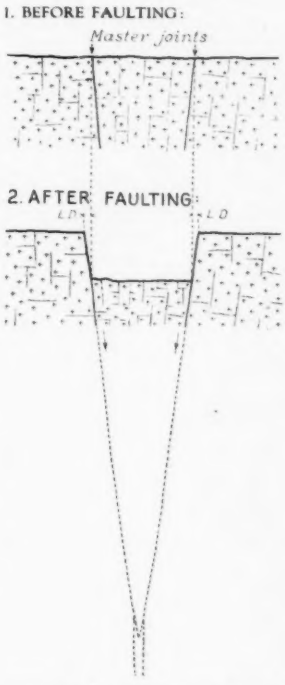

FIGURE 1.—*Diagram illustrating the probable Mechanism of simple Keystone Faulting*

During earth movements the master joints draw apart, allowing the unsupported wedge or keystone to drop. The letters L. D. represent the lateral displacement, which is small in relation to the vertical displacement.

TYPE EXAMPLE: PURGATORY, IN SUTTON, MASSACHUSETTS

The first example of the geologic structure here designated the keystone fault to attract our attention is the chasm called "Purgatory," in

Sutton, Massachusetts. This was visited by the senior writer in 1883 and described the same year in the Proceedings of the Boston Society of Natural History.[2] Since this account is probably not well known to geologists, and since the Sutton Chasm proves, on comparison, to be an exceptionally normal example of the keystone fault, it appears advisable to reproduce it here and to recognize this chasm as the type of its class.

"Purgatory, in Sutton, Massachusetts, like the places bearing the same trivial name in various other parts of New England, is a well defined chasm or gorge. It is situated in the southeastern part of the town, and is cut out of the southwestern flank of a broad, rocky and wooded hill. This chasm is quite straight, about one-fourth of a mile long, 50 feet wide, and has a northeast and southwest trend. The walls are vertical, vary in height from 10 to 70 feet, and are composed of a massive, micaceous gneiss, which is the prevailing rock of that region. The bottom, or floor, of the chasm is encumbered to an unknown depth with large, angular masses of the gneiss. The gneiss dips to the northeast about 25 degrees, and is traversed by two well-marked systems of joints, one system running northeast and southwest, or parallel with the chasm, and the other in a direction at right angles to this.

"The only explanations of the origin of the Sutton Purgatory which I have seen are the two suggested by Dr. Edward Hitchcock in his report on the Geology of Massachusetts. The first, which he rejects as being too violent and as unsupported by the disposition of the gneiss, which does not dip away from the chasm, supposes the chasm to have been produced during a local uplift of the strata.

"According to the second hypothesis, which Doctor Hitchcock was inclined to accept, this chasm is similar in its origin to the Purgatory at Newport, Rhode Island—that is, it is the product of marine erosion at a time when the sea occupied the surrounding valleys.

"It appears to me, however, after an examination of the ground, that the second supposition is even more untenable than the first. At no point do the walls of the chasm show the slightest trace of water action and the floor, instead of being bare and smooth, or covered only with rounded and waterworn boulders and pebbles, is piled with huge, angular blocks of gneiss. The same facts, as well as the situation of the chasm on a hill and not in a valley, are fatal to the notion that it is the channel of some ancient river. Glaciation, also, is entirely out of the question, for the chasm is transverse to the direction of glacial movement, its walls are entirely unglaciated, and it is devoid of drift.

"The only explanation commending itself to my mind is that referring the chasm to a local subsidence. In short, I conceive that during some disturbance of this portion of the earth's crust, such as a violent earthquake, the wedge-shaped mass of rock included between two master joints converging downwards has dropped, while the rocks were in a state of tension, to a depth of 100 feet, more or less, thus giving rise to the chasm.

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[2] W. O. Crosby: Proc. Bost. Soc. Nat. Hist., vol. xxii, pp. 434-436.

"This explanation is in harmony with all the facts observed. The chasm, as previously stated, is parallel with a well defined system of joints, and its walls are evidently joint planes. No erosion is required and evidences of erosion are entirely wanting. The angular blocks with which the bottom of the chasm is filled are just such as would naturally be produced by such a catastrophe as is here conceived. Finally, there can be no doubt that parallel master joints frequently do converge downward; that during the passage of an earthquake the rocks are thrown alternately into states of powerful tension and compression; and that, since earthquakes are of almost annual occurrence in New England, we may fairly suppose that they are sometimes sufficiently violent to accomplish results such as are here ascribed.

"The dislocation here appealed to as a cause of the chasm is one that geologists will recognize as what might be called a normal form of geological accident. In Jukes' Manual of Geology it is regarded as the best explanation of normal faults. The fracture bounding each side of the wedged-shaped mass which slips down is necessarily a normal fault.

"The facts observed also furnish a clue to the geological age of the chasm. However formed, it must be of postglacial origin; for, lying across the path of the ice-sheet, it would, if antedating the Glacial epoch, have been scraped full of glacial detritus, whereas it is singularly free from such material. The ice-sheet swept the till from this elevation, leaving it bare and rocky; and then at some subsequent period the chasm was formed, as explained.

"It is a common but evident error to refer all such geological events to some remote period; and I have seen nothing inconsistent with the view that Purgatory, in Sutton, is, geologically speaking, of very recent origin, being, perhaps, only a few centuries old."

The terminations of the chasm are not so clearly indicated as could be desired, but the appearances are that toward the northeastern and higher end the walls converge and meet in an edge, as previously pointed out, while in the opposite direction divergence of the walls is suggested, as the chasm dies out in a broad and somewhat swampy valley.

Other geologically recent Examples

General statement

"Geologically recent," as the term is employed here, implies that the phenomena are of postglacial origin; and these examples, it is obvious, must be the clearest in their geologic relations. Therefore we pass now to the consideration of other more or less typical examples of the keystone fault widely scattered over the region covered by this investigation to date—New England and contiguous territory. Again the elder Hitchcock leads the way and accurately describes the phenomena; but once more, also, he fails to assign an adequate or acceptable explanation.[3]

[3] Hitchcock: Final report, 1841, p. 296.

PURGATORY, IN GREAT BARRINGTON, MASSACHUSETTS[4]

"A fissure very similar to that in Sutton exists in the mountain east of the village of Great Barrington. The best way to reach it is to pass around the north end of the mountain, Warner Mountain, and then to go southerly a mile or two, as far as the house of Russell Kilbourn, from whence a walk of three-quarters of a mile will lead to the spot. It is an open fissure, about 4 rods wide, with perpendicular walls which in some places rise to the height of 80 feet. The bottom in most parts is strewed over with loose but not rounded blocks, which were obviously derived from the sides. This detritus frequently fills up the bottom several feet, so that probably the entire depth can not be much less than 100 feet. Among the loose masses of rock, snow and ice frequently remain through the summer. I found them there in abundance on the 25th of June, on a very sultry day.

"This 'Purgatory' is in gneiss, which a good deal resembles that in Sutton. The strata in Great Barrington are nearly horizontal, and the fissure is nearly straight; but at its western extremity the sides rather diverge. It runs south 25 degrees west and north 25 degrees east and extends across the entire ridge of the mountain, at least 80 rods in length. Its bottom can not be less than 800 feet above the bed of the Housatonic. I can mention no explanation of the manner in which it has been produced, except the one suggested in regard to the Sutton Purgatory, and which will, I think, receive some illustration from certain fissures on the coast of Rhode Island, which I therefore introduce in this place. To persons, however, who are but little familiar with geological changes, probably the explanation which I give of these so peculiar phenomena will seem no better than wild hypothesis."

The gneiss is in large part banded and thin bedded or platy. The prevailing dip is low to the northeast. The boulders are all angular and average rather small, owing to close jointing of the gneiss. The length of the chasm is fully one-half mile and it is remarkably straight. The walls are vertical or slightly converging downward and plane, except where they have slumped. The width of the chasm is not uniform, varying from 30 to possibly 100 feet and widening southward.

The trend of the chasm is distinctly transverse to the glacial trend for the region, and glacial drift of every description is conspicuous by its absence, while we look in vain for even the faintest indication of either glacial or aqueous erosion. The opposite walls are in general about equal in height and definition.

In brief, the Ice Gulf, or Purgatory, of Great Barrington is a close duplicate of the Sutton Purgatory, presenting the same features, though on a somewhat larger scale, and clearly requiring the same general explanation.

[4] Known locally as Ice Gulf.

ICE GLEN, IN STOCKBRIDGE, MASSACHUSETTS

Although this may not be a strictly typical or normal keystone fault, it appears to be, at the least, a closely related structure. For its location and topographic environment see the southeast corner of the Pittsfield Quadrangle, where its name will be found on the south side of the Housatonic River, south and southeast of Stockbridge Village. It is now a public park, and hence readily accessible. It is about a quarter of a mile long in a northeast-southwest direction, and at an elevation of about 1,000 feet it tends to isolate the northwest end of the Laura Tower ridge or spur of Bear Mountain.

The rock is a very massive, fine-grained gneiss, and hence the boulders, which are wholly angular, tend to be large, maximum diameters of 10 to 20 or more feet being not uncommon. There is no well-defined chasm with vertical walls matching the Purgatories; but the large, angular boulders extend in pell-mell fashion up the opposing slopes, which are precipitous to the northwest and steep to the southeast. One suggestion is that in this instance the broken rock resulting from the crushing of the keystone proved to be more than sufficient to fill the chasm. This excess in volume of crushed rock, it is surmised, is a common occurrence and tends to obscure the phenomena.

Still another explanation of Ice Glen we have in the suggestion of two widely flaring master joints, the resulting keystone being broad and shallow rather than narrow and deep, the breadth, in fact, being more or less indefinite, according to the distance the crushed rock may have been shoved up the opposing slopes. As with the Purgatory chasms, the post-glacial origin of Ice Glen is unmistakably clear, made so by the uniform character of the broken rock, its restricted distribution, and, as for the Purgatories, by its independence of the glacial trends.

TOPHET SWAMP, IN LITTLETON, MASSACHUSETTS

Although this example, to which our attention was first directed by Prof. George H. Barton, is not to be found on any available map, we recognize it as a typical keystone, meriting both a name and a contour, or, better, several contours. Referring to the southeast quarter of the Groton Quadrangle, the locus of this keystone may be defined as the small valley opening to the northeast nearly three-fourths of a mile from Littleton Station, on the road to Ayer. The conventional lateral valley which the map shows is certainly a very inadequate expression of the actually existing rectangular, abrupt-walled depression. The gorge opens to the northeast, on the farm (Idlewild) of I. E. Nixon. Geologically, it

appears to be wholly included in the long, narrow belt of the Brimfield schist (see Emerson's geological map of Massachusetts and Rhode Island), and it is noteworthy that the strike of the schist and the trend of the depression closely coincide.

Tophet Swamp floors a gorge about half a mile long, with an approximate southwest to northeast trend. It is about 300 feet wide and closed at the southwest end, and 500 feet wide and open at the northeast or downstream end. The floor of the gorge is level and swampy—almost a lake—and it is reported that a sounding rod was driven to a depth of 19 feet. The southeast bluff is slightly the higher, reaching its maximum elevation of about 100 feet midway of its length. Southwesterly the gorge terminates abruptly, as if cut off by a transverse fault. Midway of this end, and about 50 feet above the swampy floor of the main gorge, a small gully opens into the latter. This has a maximum depth of about 20 feet and extends southwesterly, on the axis of the main gorge, for a distance of 300 feet, where it gradually dies out.

At the west angle of the southwest end of the main gorge is a shorter and less regular gully. It is separated from the main gorge by a ridge, 5 to 15 feet high, of disturbed and broken bedrock. In the gully behind this ridge is a small pool of water at an elevation of 40 feet above the level of the swamp. From this pool a tiny stream descends into the swamp, flowing over ledge where it leaves the pool, which is entirely surrounded by ledge. This gully is evidently due to an offset of the main northwest fault.

The fault-scarps make definite angles with the surface of the peneplain in which this keystone has been developed, and we do not find the rounded edges or physiographic curves characteristic of subaerial erosion. The bluffs are, in the main, very steep and often rocky and precipitous, presenting in this respect a striking contrast to the smooth and gentle slopes of the neighboring ridges and valleys.

In the open northeast end of the supposed keystone gorge of Tophet Swamp no ledge is in evidence, and, as stated, none was detected by the sounding rod in the open swamp at a less depth than 19 feet, the overburden of the swamp area consisting exclusively, it would seem, of mud and silt, and the rock bottom, apparently, being below the level of the country to the northeast, following the axis of the gorge.

Especially noteworthy is the absence from the slopes as well as the floor of the gorge of any appreciable accumulation of till, excepting, of course, such till as may have antedated the formation of the gorge. Apparently we can not escape the conclusion that the Tophet Swamp key-

stone is of postglacial origin; otherwise this distinctively transverse valley should be packed with glacial drift instead of being free or almost free from drift, as we now find it.

The trend of the gorge and the strike of the schist bedrock are the same—north 50 degrees east, true—and the dip of the schist is approximately vertical. It is conceivable, therefore, that this particular keystone fault may be due in part to movement in bedding, or cleavage seams, and not exclusively in master joints. The land closing the northeast end of the swamp is firm and dry till, and seems to show that the depression caused by the faulting has terminated in this direction.

Briefly, then, each puzzling feature of Tophet Swamp and its environment finds a consistent and logical explanation in local block faulting or the down faulting of a limited area. This movement resulted primarily in the formation of a lake basin, the slow silting up to the overflow level of which has required a long time. Hence we may fairly conclude that, although the keystone of Tophet Swamp is of postglacial origin, it is not recently postglacial. In harmony with this conclusion is the general aspect of the swamp and its environing slopes. Thus we discover that Tophet Swamp is in a somewhat different class, chronologically, from the Purgatories, although due allowance must be made for the influence of water in the aging of the phenomena.

ICE GULCH, IN RANDOLPH, NEW HAMPSHIRE

In the White Mountains we have a region rich in keystone-fault phenomena; and Ice Gulch is, certainly, one of its most complete and impressive examples; also, it is one of the most accessible, and hence a good starting point for a systematic study.

Ice Gulch is located in the northern part of the township of Randolph, Coos County, on the eastward-flowing Moose Brook, which has its source in the gulch, and approximately, in due north lines, 2¼ miles north of Randolph Hill Road, at the west end, or source, of the gulch and 1⅔ miles at the east, or downstream, end. The extreme length of Ice Gulch from its source to Peboamuk Fall, where it may be considered to terminate, is about a mile and a half. The course of the gulch is, approximately, north 65 degrees west to south 65 degrees east, making, as do the Massachusetts keystones, a wide angle with the glacial trend. In its length of, say, 8,000 feet, the floor of the chasm drops from an elevation of about 2,500 feet to 1,500 feet or, roughly, 1,000 feet. The same average gradient, 1 in 8, holds for the rim of the chasm and pretty well,

also, for the general eastward slope of the land on either side of the chasm.

Proceeding now to a more detailed description, we may note that the upper end of Ice Gulch is bordered by an approximately level plain, the divide between the drainage eastward through Ice Gulch and Moose Brook into the Androscoggin River and the drainage westward through minor tributaries into the Upper Ammonoosuc River and the Connecticut. This is, therefore, a point on one of the most important divides of New Hampshire and New England. The bedrock of Ice Gulch is granitic, of varying texture and composition (Winnipiseogee gneiss of Hitchcock).

Beginning somewhat abruptly, the chasm gradually expands by the divergence of its approximately vertical walls, attaining in the first 800 feet an estimated depth of 75 feet and a top width of about 200 feet, or not to exceed 250 feet from rim to rim.

The upper walls are precipitious and very broken and shattered, and the lower walls are concealed by heavy talus of broken blocks. The bottom width of this part of the chasm, if there were no talus, would probably not exceed 100 feet.

This first 800 feet of the gulch is known as the Vestibule, and at the lower end of this section the floor of the gulch drops abruptly over 100 feet, probably 150 feet, into the Expansion of the Vestibule, 600 feet long. The north wall is here offset to the north at least 200 feet to form Sargent Cliff.

At the end of the 600 feet comes the First Chamber, 300 feet long. The drop into this chamber is rather gradual and about 50 to 75 feet at the lower end of the chamber. The estimated normal breadth of the main part of the gulch, between the vertical walls, is 300 to 400 feet. About midway of the length of the gulch the walls draw nearer—say 200 feet—and the angular blocks of granite are piled up 40 or 50 feet above the normal floor level, forming a topographic dam of that height. On this dam is, perhaps, the largest block in the gulch, approximately 40 by 20 by 15 feet.

The bedrock floor of the gorge and the stream flowing on it are nowhere exposed to view, but it can hardly be less than 200 feet below the sharply defined rim and may be considerably more than that. This difference of level, whatever it may be, measures the throw of this keystone fault, which dies out westward by the convergence of its walls, and eastward, it is probable, by the transverse faulting to which we owe Peboamauk Fall.

It is important to compare the fall escarpment with that at the lower end of the Vestibule. The latter can not be thought of as the product of stream erosion, nor of ice erosion in such a narrow valley and so near its head. This gorge is piled high with angular blocks of the granite of its walls; but glacial drift is conspicuous by its absence, and we find no ground whatever for the view that this gorge or any part of it is a glacial cirque. On the contrary, it is a clear instance of the dropping, when released by earthquake tremors, of an unsupported wedge or free sphenoid of the terrestrial crust.

THE DEVILS HOP-YARD, IN STARK, NEW HAMPSHIRE

This example, to which our attention was first directed by Prof. Arthur Stanley Pease, is on the headward portion of the brooklet originating in the col on the south side of Mill Mountain and tributary, in a little more than a mile from its source, to the south end of Percy Pond. The lateral walls of the upper half of this little valley are abrupt and rugged, and the chasm thus derived is divided in its upper part by a precipitous escarpment more than a hundred feet in height. From the south side of the upper reach of the chasm juts a bold headland, due to a local change in the trend of the chasm from northeast above this point to approximately east-west below it. The difference in elevation of the upper and lower ends of the chasm, or the total fall, is, roughly, 300 feet.

The bedrock is granitic (granite porphyry of Hitchcock) and very massive. Owing to the rather widely spaced joints, the angular blocks encumbering and concealing the floor of the chasm are exceptionally large, this being a principal point of contrast between Ice Gulch and the Devils Hop-yard. We may note, however, that, taken as a whole, Ice Gulch is the larger, and especially it is the longer, chasm. The transverse escarpment of the Hop-yard, comparable with the drop at the lower end of the Vestibule in Ice Gulch, is distinctly the more impressive feature. The general trend of the Hop-yard chasm is, roughly, north 70 degrees east, or almost squarely across the course of glaciation, and once more we must recognize the probability or practical certainty that the phenomena in question are of postglacial origin.

LARY FLUME, IN SHELBURNE, NEW HAMPSHIRE

Lary Flume, on Success (North Baldcap) Mountain, in Shelburne, New Hampshire, is a typical keystone fault gorge, similar to Ice Gulch. It is about half a mile long, up to 100 feet deep, 50 to 100 feet wide in the lower part, but narrowing to 10 feet in the upper part, where it dies

out at the top of the pass between Success Mountain and the next summit to the east. It is widest midway of the length and a little narrower at the lower end, where it gradually changes from a distinct fault gorge to a narrow valley of normal form. The walls are vertical or slightly converging downward. The floor is a jumbled mass of angular blocks of medium-grained granite. There is no glacial drift. This fact and the sharp angularity of the granite blocks prove that the gorge is of post-glacial origin. The trend of the gorge is constantly north 10 degrees east, true, obliquely across the glacial movement for the region, furnishing additional proof of a non-glacial origin for many keystones. A small stream flows from the gorge, but is obviously inadequate to its formation.

Examples Transverse to elevated Ridges

This is a fairly common and characteristic relation, the keystone fault taking the form of a miniature box canyon or well-defined chasm cutting squarely and entirely across the crest of a high, bare ridge. Several examples have been noted and seem to warrant separate classification.

On the crest of the Mahoosuc Range, north of Goose Eye Mountain, in the town of Riley, Maine, and also south of this summit, are several of these sharply defined, transverse box canyons, or chasms, cutting the crests to maximum depths of 50 or more feet. These abrupt breaks in the continuity of the crests are negotiated with some difficulty by the mountaineer; also, similar gaps occur in the crest of Sunday River White Cap Mountain, and many others, it is believed, await discovery or recognition, notably in the vicinity of the principal mountain notches, in the formation of which they may have played an important rôle.

Turning now to more detailed observations, we note that three box chasms, or miniature canyons, cross the ridge between Mounts Ingalls (Success) and Carlo. The southernmost and most representative of these is about 20 feet deep and 40 feet wide between precipitous walls. It heads in the crest of the range and runs easterly down the mountain an unknown distance. The bottom is strewn with large, angular blocks. The second example has a deep fissure at the foot of its north wall, which is 30 feet high.

At the north foot of the cone of East Goose Eye is a box canyon about 30 feet wide, with walls 10 feet high on the north and the full height of the mountain on the south. It runs across the ridge at right angles to its axis.

Midway of the plateau between East Goose Eye and North Goose Eye

is a chasm about 50 feet wide and 30 feet deep and trending north 65 degrees west.

Just below the Full Goose Camp and in the saddle between North Goose Eye and Fulling Mill Mountains is a smaller chasm, 15 to 20 feet wide between vertical walls and 5 to 10 feet deep.

On the northern shoulder of Sunday River Whitecap Mountain, in the town of North Newry, Maine, is a box canyon extending east and west across the ridge. It is approximately 50 feet wide and 20 feet deep.

Notches of the White Mountains

General statement

Having considered at length keystones developed on the general crystalline and peneplained floor of New England, and, more briefly, those cutting the elevated crests and ridges of the mountainous areas, we pass now to the consideration of those notching the bottoms of the deepest gaps of the mountains.

Grafton Notch, Maine

This notch, some 2,000 feet in depth, divides to its baselevel the northeastern, or Maine, section of the White Mountains. Although we may well hesitate to ascribe this and similar profound notching of the ranges exclusively to keystone faulting, or even to postglacial time, we can not doubt that faulting of some type has played an important part in the physiographic development of the region. The general trend of the notch is approximately north-south, and it clearly does not make so wide an angle with the glacial trend as to negative the conclusion that the notch is due in part to glacial erosion. The influence of keystone faulting is manifest, however, in the deep and narrow longitudinal chasms trenching the bottom of the notch. Two such chasms are in evidence, both on the southerly, or Androscoggin, slope of the range. But, whatever may be thought of the origin of the notch as a whole, it seems certain that to neither stream erosion nor glacial erosion may fairly be attributed the principal agency in the formation of the chasms.

The most northerly of the chasms, and the one nearest the summit of the notch, is known locally as Moose Cave. It is over 200 yards long, more than 50 feet in extreme depth, and 5 to 20 feet wide between vertical or overhanging and shattered walls, from which many large, angular blocks of the granitic bedrock have fallen. Glacial drift of every description is wholly wanting and the postglacial origin of the chasms appears to be a safe assumption.

The second, or lower, chasm, known locally as Mother Walker Falls, is a short distance to the southward of Moose Cave. It is about one-fourth mile long, a hundred feet deep, and 10 to 60 feet wide. The rock is even more shattered than in Moose Cave, and yet the bottom is encumbered by many large blocks, and the solid floor can nowhere be seen, the depth to which the chasm is filled being mainly a matter of conjecture.

In both chasms the cliffs, at some points, descend vertically into standing water. The chasms are, on the east, close against the precipitous wall of the notch, and on the west side the gentler slope is broken longitudinally by several incipient faults, this wall of the chasms dropping in a steplike fashion. That these chasms are due to diastrophic causes we can not doubt, and that these or similar rifts have played an important rôle in the formation of the giant notches appears to us most probable, as previously noted.

MAHOOSUC NOTCH, MAINE

The Mahoosuc Range extends southwesterly from Grafton Notch, Maine, to Gorham, New Hampshire. Cutting the northeastern part of this section of the White Mountains is Mahoosuc Notch, a great cleft, half a mile long, several hundred feet wide, and 500 feet deep between precipitous walls, and trending directly across the course of glacial movement. The bottom of the notch is a confused, pell-mell aggregate of huge, angular blocks of granite, with no sign of ledge in sight. Since the notch is at the drainage divide, no stream courses through it. Hence water erosion is even more inconceivable than ice erosion as a possible cause of Mahoosuc Notch, the most impressive, perhaps, of this series of keystones.

CRAWFORD NOTCH, NEW HAMPSHIRE

This famous notch, a few rods below the source, in Lake Saco, of the southward-flowing Saco River, is remarkable for the fact that in the Gateway, the very axis of the notch, the infant river is lost for some 600 feet in a very obvious fracture or system of fractures. In fact, we have here a possible zone of fracture extending from the precipitious face of Elephant Head westward across the highway and railway or the entire breadth of the Gateway, about 100 feet, more or less. The opposing bluffs of parallel strike but converging dip, approximately 150 feet high on the Elephant Head side and 100 feet high on the Mount Willard side, are the limits of the principal keystone of Crawford Notch. The shattering effect on the keystone of the compressive stress which its position implies is most strikingly exhibited in the immense, rectangular and

somewhat isolated blocks of granite which encumber the gorge immediately below the Gateway and between which the stream meanders and is partly lost.

The summit of Elephant Head is flattish and 130 feet wide between its boundary cliffs—150 feet high to the westward (toward the axis of the notch) and 40 feet high to the eastward (toward Mount Clinton). Evidently there is an auxiliary, or secondary, keystone east of the notch, and this is clearly repeated to the westward, for the summit of the 100-foot cliff bounding the main keystone in this direction is also flattish for a narrow breadth before dropping sheer 10 to 30 feet. The special interest, then, of this example is found in its probable composite character; and to this may be added the probability that it is of preglacial origin, although this point requires further investigation.

DIXVILLE NOTCH, NEW HAMPSHIRE

This well known notch, the only available gap between the Connecticut and Androscoggin drainage systems in a stretch of many miles, presents an interesting study. First, as to the agent: Was it water, ice, or diastrophism? We must recognize at the outset, however, that, whatever the origin, this is topographically, like Mahoosuc Notch, a wind gap and not in any true sense a water gap, although it is the source of two notable streams—Mohawk River, flowing westward a dozen miles to the Connecticut, and Clear Stream, flowing eastward a like distance to the Androscoggin. Conclusive evidence that this notch has ever been occupied by a through stream in either direction appears to be wanting; but it may be noted that the bedrock of this part of the Dixville Range is a fissile, semimetamorphic slate or phyllite, the Lyman group of Hitchcock, presenting a striking contrast to the massive granitic rocks of the preceding examples. The phyllite is of such nature that it must yield rather readily to aqueous erosion, and streams in it are likely, therefore, to develop relatively deep and narrow head ravines. If, now, streams on opposite slopes of this exceptionally narrow part of the range coincide in position, a continuous gap, or notch, naturally results, though not cutting quite to the baselevel or the level of a true water gap.

Although a more or less plausible argument for an erosion gorge or chasm is thus within the range of possibility, we are well convinced that the preponderance of evidence is, after all, with the diastrophic or seismic agencies, and that Dixville Notch is due to a local subsidence with or without the accompaniment of earthquake tremors. If we refer its origin to any form of erosion, local subsidence must apparently still be postu-

lated to account for Table Rock and other semidetached and highly salient spurs and for Ice Cave.

As calculated to throw light upon the origin of the notch we have, also, the significant facts: that such marked postglacial erosion has not been noted elsewhere in the Dixville Range; that the contours are wholly unlike those due to glaciation; that till and all well identified forms of glacial drift are wanting; and that the notch is obliquely transverse to the glacial trend.

Related Phenomena

General statement

These are the rifts and fissures, chiefly of postglacial origin, which may be regarded in general as partial or incipient keystones, with earthquakes as the cause most commonly assigned. We regard earthquake rift as a good general caption under which to classify them, and two examples only will be cited here. The first of these is described by T. Nelson Dale in his second paper on "Structural details in the Green Mountain region and in eastern New York,"[5] in part as follows:

Caves formed by tension and rupture

"About half a mile northeast of the extreme southwest corner of the State of Vermont and of the town of Pownal, on the eastern side of the Taconic Range, the Ordovician schists are fissured in a direction parallel to the prevalent transverse jointing of the region. These fissures or joints strike north 75 degrees–80 degrees east and dip 90 degrees. Between two of these a mass of rock 10 feet wide has been faulted down (an obvious keystone). At another point the schists, which are noncalcareous and veined with quartz, have been parted along the foliation, forming an irregular fissure from 1 to 5 feet wide and more than 130 feet deep. Such a cave is evidently due to tension of the schist mass normal to the foliation." (The parenthesis is ours.)

The second example, Gothams Cave, on Porter Mountain, on the eastern side of Maidstone Lake, in the town of the same name in northern Vermont, is a complex network of irregular fissures in the hard schist bedrock, familiar to the writers and described by Hitchcock.[6] The fissures are vertical or steeply inclined, average three feet in width, and are referable to two systems, longitudinal and transverse, the former, the more prominent, trending northwesterly up the hill, and the latter at right angles to this. At the intersection of two fissures there is a chamber 16 by 22 feet.

[5] U. S. Geol. Survey Bull. 195, pp. 11-12.
[6] Proc. Am. Assoc. Adv. Sci., vol. 44, 1896, p. 133.

The fissured zone is roughly 40 to 50 feet wide and has been traced obliquely down the hill for about 400 feet. Some 600 feet farther in the same direction, at the foot of the slope, is a very clear, cold and strong spring, the source of which must be in the annual accumulations of snow and ice, to be seen even late in the summer in the deeper fissures of the fractured zone.

Evidence of faulting is not very marked, but the southwest wall of each principal fracture is a foot or more lower than the northeast wall, and it is clear to our minds that we have in Gothams Cave an incipient or arrested development of one of the more important keystone faults.

Summary of dynamic and structural Relations

The earthquake vibrations of the terrestrial crust must tend to shake down and crush the potential keystones. Beneath the keystones void spaces tend to persist, and the distinctness and size of the voids will vary with the form and crushing resistance of the keystones. Rarely are the keystones sufficiently obtuse to insure their elevation by lateral pressure, but we have, perhaps, an exception to this rule in Ice Glen, in Stockbridge, Massachusetts (page 629). Hence a true keystone is in general indicative of the opening of converging master joints during tension, the dropping of the included wedge and its crushing, at least superficially, during the ensuing compression phase of a complete oscillation. Finally, the deep-seated void accompanying the development of a normal keystone, with the attendant transfer from rock pressure to hydrostatic pressure, must be regarded as favoring in a marked degree the deposition of dissolved minerals and the formation of ore deposits.

Appendix

Acknowledging such constructive criticism as has come to hand, it may be granted that, although keystone faults are not essentially distinct, either structurally or dynamically, from the narrow-block or trough faults, a distinctive name appears, nevertheless, to be desirable, for the reason that this type is found to be exceptionally rich in geologically recent examples, at least in the New England field.

As to the appropriateness of the name, it may be noted that arches, both natural and artificial, may be very flat, especially when well buttressed or supported by the continuously solid substructure of the ledge; also, we need not overlook the fact that the earth's crust is an arch to which master joints are usually normal, and hence convergent down-

ward. Or, again, we may conceive the keystone as existing only potentially until the earthquake vibrations open its boundary joints, when the keystone stands out, momentarily, with the utmost distinctness and all the thrust that the name implies. An alternative or substitute name of similar signification may be found in the term "wedge" or the descriptive phrase "sphenoidal fault"; but neither impresses us so favorably as the keystone.

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PHYSIOGRAPHY OF THE CALIFORNIA COAST RANGES[1]

BY ROBIN WILLIS

(*Read before the Geological Society December 29, 1924*)

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[1] Manuscript received by the Secretary of the Geological Society April 15, 1925.

Introduction

The California Coast Ranges, from the region around Santa Rosa north of San Francisco Bay to the San Fernando Valley near Los Angeles, and between the San Joaquin Valley and the coast, offer an

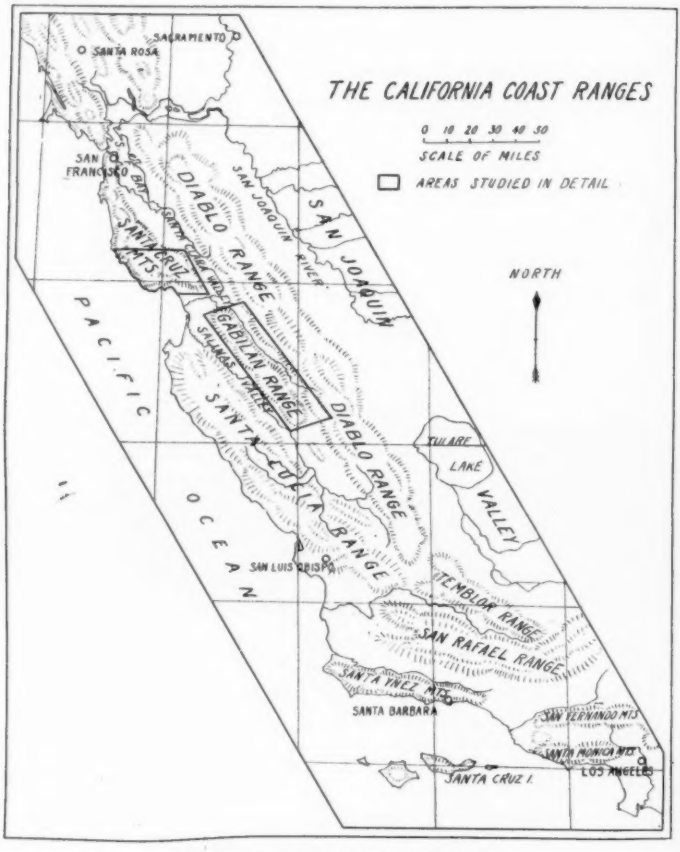


FIGURE 1.—*Coast Ranges of California*
Showing the principal ranges and the areas studied.

unusual and interesting type of physiography. The region may extend south into the peninsular ranges as well as north of Santa Rosa, but the author knows of no other ranges of this type in this country.

The material for these notes was obtained in studies connected with the work of the Seismological Society of America in locating the active faults of the Coast Ranges. One summer, 1922, was spent in general reconnaissance work covering a good part of the region between Santa Rosa and San Luis Obispo. The autumn of the previous year, 1921, was spent in a detailed study of the southern Santa Cruz Range and the summer of 1923 in a similar study of eighty miles of the San Andreas Fault along the Gabilan Range. In this paper examples will be taken largely from the last of these regions. The writer has also worked in the region northwest of Los Angeles and in the Santa Ynez Mountains, both of which show similar physiographic types.

FIGURE 2.—*Salinas Valley from the Summit of Santa Lucia Peak*

View looking northeast to the valley. The mature topography in the foreground is typical of the older Coast Ranges. The Salinas Valley is a down-faulted block.

TYPES OF RANGES

PROCESSES CONTROLLING THE DEVELOPMENT OF THE RANGES

The mountain ranges in the region outlined are strictly tectonic mountains. Their broader features are controlled by differential uplift due to deformation of the underlying rocks, as opposed to uniform uplift, where the topography is controlled by differential erosion.

The deformation of the Coast Ranges is of an unusual type. It is controlled by the movements on the great faults of the region, folding being secondary. Many of the ranges are simple fault-blocks, but folding also has its influence on the broader features. Even in massive rocks the

blocks may be deformed by compression, thereby warping their surfaces. The more detailed features of the Coast Ranges are not the result simply of differential uplift, but also of differential erosion. The Coast Ranges vary widely as to age, as has been pointed out by Dr. Mendenhall[2] in the case of the San Gabriel and San Bernardino Mountains. The secondary features of the older ranges are due almost entirely to differential erosion. Here the larger eminences are composed of the harder rocks, and the stream systems are adjusted to the underlying structure. These ranges are so maturely dissected as to reveal only one cycle of erosion, as all evidence of previous cycles has been destroyed. Only in their major outlines can the effects of the faulting be seen in such ranges.

FIGURE 3.—*Youthful Canyon developed in a mature Upland, due to Uplift*
A tributary of the San Benito River south of Hollister, in the Bird Creek Hills.

The central part of the Santa Lucia Range is of this type, as is shown in figure 2.

The younger ranges show features due to two erosion cycles—an upland of late mature topography, with wide valleys and rounded hills, much farther advanced in the cycle than the older ranges just mentioned, and dissecting this upland a number of youthful canyons.

Figure 3 is an illustration of this contrast on a small scale. In such a range *differential uplift*, due to faulting, bulging of massive rocks, or folding, controls the minor features of the range. The stream system

[2] W. C. Mendenhall: Two mountain ranges of southern California. (Abstract.) Bull. Geol. Soc. Am., vol. 19, 1908, pp. 660-661.

in the new cycle shows consequent characteristics rather than adjustment to lines of weakness, and the higher points are those of maximum uplift. The details of the older surface are, of course, controlled by differential erosion, but the relief of this surface is generally much less than that of the range as a whole.

It is in this type of range that the effects of differential uplift on the topographic surface can be studied, and this is the type considered in this paper.

EFFECTS OF DEFORMATION

The effects on the topographic surface of deformation in the underlying rocks of this region may be classified as the direct effects of faulting, namely, uplift and production of fault-scarps, and the effects of the deformation of the fault-blocks, namely, tilting and warping. The last may be due either to folding in sedimentary or bulging in massive

FIGURE 4.—*Plateau of Quarternary River Gravels near Tres Pinos*

The rocks underlying the rolling hills in the foreground are resistant early Tertiary sandstones. The difference in stage between the youthful plateau and the mature hills, with the latter in more resistant material, suggests that the bluff is probably a fault-scarp modified by the action of the stream.

rock. Any one of the foregoing produces differential uplift which results in *different rates in the development of the erosion cycle,* either in adjoining blocks or within the same block. Where such discordance or difference in development is still found after all other factors, such as differential erosion, climate, and drainage, have been considered and eliminated, it is proof of tectonic activity, and in the Coast Ranges it indicates the possibility of active faulting. Figure 4 shows a typical case.

TYPES OF SURFACE

Classification.—The types of surface found as a result of such uplift are four: uplifted but undeformed erosion surfaces, tilted surfaces, warped surfaces, and surfaces of deposition. The last named type is

considered in the next main section. The principal criteria for distinguishing between the others are found in the character of the topographic unconformity, the profile as seen in the skyline, and the stream system.

The uniformly uplifted surface.—Surfaces which have been uplifted without tilting or deformation are characterized by a sharp topographic unconformity or angular break between the surfaces produced by the two erosion cycles. Above this break in the slopes are found old undisturbed

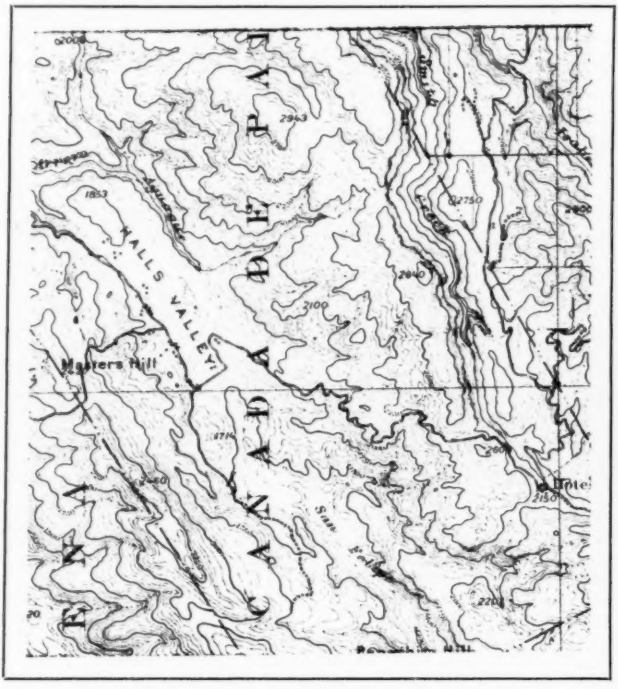


FIGURE 5.—*Part of Mount Hamilton Quadrangle*
Note the mature character of Hall Valley, as contrasted with the young canyons of Arroyo Aguaje and Smith Creek.

valleys with streams still flowing at grade. If the block had been tilted or deformed during uplift, the processes of the old cycle would have been disturbed throughout the area and no such old high-level valleys would remain. The rejuvenation of a uniformly uplifted surface takes place by a process similar to headwater erosion, working back along the streams from the edges of the uplift. The distance from the edge reached by the

rejuvenation is proportional to the size of the stream and its fall. The stream pattern undergoes little modification except near the scarps. The profile of the skyline is that of the old cycle until maturity is reached, when its irregularities become accentuated. The summit of Mount Hamilton Range, of which a section is shown in figure 5, is a good example of this type of uplift.

The tilted surface.—The most characteristic feature of the tilted surface is the tendency shown by the stream system in its development. If the streams of the new cycle have gained complete control, the system will be made up of new consequent streams, or of streams inherited from

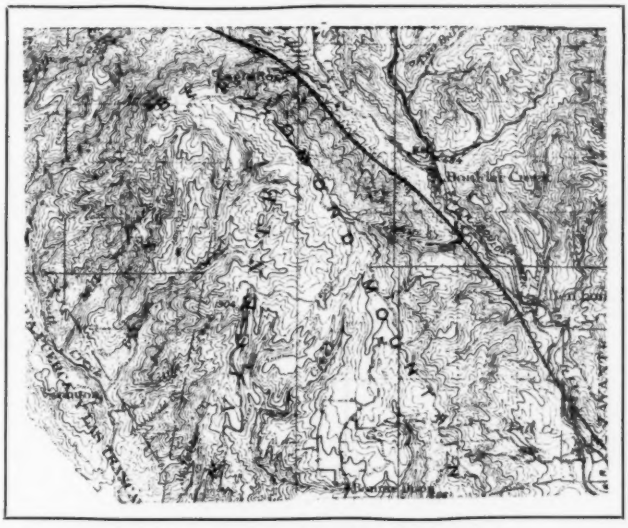


FIGURE 6.—*Part of the Santa Cruz Quadrangle*

Showing the tilted block of Ben Lomond Mountain and the fault on the east. The long streams like Mill Creek have consequent courses down the back slope of the block.

the previous cycle favored by the uplift, resembling consequents in their characteristics. If the relief of the old surface was great, and strong streams flowed on it, the tilted block will show a system wherein the youthful streams will reveal a tendency to capture the subsequent streams of the old system.

On a tilted surface rejuvenation takes place immediately throughout the length of the streams which flow down the slope. The only high level valleys found undisturbed will be those parallel to the axis of tilting. Streams flowing against the slope silt up their valleys. The topographic

unconformity between the two cycles is irregular and hard to trace, depending for its position on the direction of the stream rather than on the distance from the edge of the block. The profile of such a block generally shows the tilting. If the profile is very irregular, the residual

FIGURE 7.—*Mount Tamalpais from San Francisco Bay*
Note the steep slope on the right and the long, gentle, uniform slope on the left.

eminences are apt to show asymmetry due to the tilting. An example of a tilted profile is shown in figure 7.

The arched surface.—The arched or warped surface, on the scale here discussed, is a feature peculiar, so far as the writer knows, to regions of

FIGURE 8.—*Small but perfect arched Surface near Loma Prieta, in the Santa Cruz Mountains*
Note the smooth curve on the right and the destruction of the profile on the left, where the dissection of the surface is reaching maturity.

recent tectonic activity like the Coast Ranges of California. The arches vary from two to ten miles or more in width. The smallest one noted is about one and a half miles across (see figure 8). This is exceptional. The Gabilan Range, a fine arch, is about ten miles across. The ranges

often show an arched profile longitudinally as well as at right angles to their axis. This may be much more than ten miles in length.

These arches are first noted because of their profile. The two chief characteristics of it are its smoothness and its lack of inflection points (see figures 8 and 9). The profile comes down to the foot of the arch without flattening off at the bottom, as do convex erosion profiles. It is striking for this reason, and when seen on a single range rising above a plain, as is the case in some of the Coast Ranges, it is immediately noted.

The question arises, Can such a profile be produced solely by erosional processes? The answer is, except in unusual instances, No. The evi-

FIGURE 9.—*Arched Profile of the southern Continuation of Montebello Ridge northwest of Los Gatos*

dence for this statement is that the visible processes are working to destroy the arch, no matter what stage of dissection has been reached in the present cycle. As the streams cut down their valleys, and two adjacent systems of consequent streams cut away the divide between, the tendency is to produce a profile concave upward. This is seen in the spurs to the left in figure 8. Though a minor spur between two converging streams may take on a convex profile, the larger ones between drainage systems do not, and it is these that are seen in looking along a range. When maturity is reached and the whole range is rounded off, the profile will be convex, but it will not reveal the smooth, unbroken curve shown by arches due to deformation.

The profile, however, is not considered sufficient evidence to justify

the unquestioned acceptance of the warping of the surface. Other evidence is found in the stream systems and in the nature of the topographic unconformity. In young arches the streams show rejuvenation on the lower slopes similar to that on steeply tilted surfaces, but farther up one finds a sharp topographic unconformity, above which are undisturbed valleys belonging to the older cycle, similar to those found on uplifted surfaces, though of less extent. The topographic unconformity is sharp, the range young, yet the profile in no way suggests a fault-scarp. The only explanation of this combination of features is warping. The Gabilan Range furnishes an excellent example of this kind. One may go even farther with the argument. In the southern part of this range, in Gloria and adjacent valleys (see figure 22), there are streams which rise west of the axis and flow east. Their valleys have been silted up at their heads, due to the tilting against grade on the west side of the arch. On the crest the old valleys are undisturbed, while still farther east they are rejuvenated.

It may be noted that the Gabilan Range is composed of granite and metamorphic rock. It is not a single fold in sedimentary rocks; the arching is due to bulging.

DISCUSSION OF THE TYPES OF RANGES

The three types of surface just considered, together with fault-scarps, are combined in various ways to make up the individual units of the Coast Ranges. One may find true horsts on which are undisturbed old surfaces with a scarp on either side. This is rare. The tilted block is more common. The area southeast of the Gabilan Range is such a block; another is Ben Lomond Mountain, north of Santa Cruz, illustrated in figure 6. There are also a few cases of simple warped blocks which come down to a plain or to a fault-line on either side. The "foothills" of the Santa Cruz Mountains between Palo Alto and San Francisco may be of this type. The majority of the larger ranges are more complex. There are two types. Those that may be termed regular consist of definite blocks, well defined by faults. Each of the blocks has been deformed as a unit, either being uplifted, arched, or tilted uniformly throughout, though sometimes combining two of these features. The irregular ranges may show a variety of surface types on one block. The fault-lines are less continuous and the blocks less clearly defined. There appears to be some connection between the underlying rocks and the type of range. Those underlain by the Santa Lucia granite and associated rocks are usually regular, those underlain by the structurally heterogeneous Franciscan are generally irregular. Not enough work has been done, however, to permit the statement of this as a definite rule.

Of the regular ranges, the Gabilan Range is a combination of an arch on the west, which comes down to the floor of the Salinas Valley, with a fault-scarp combined with some arching along the San Andreas fault on the east. The Diablo Range, near Mount Hamilton, has a complex scarp on one side and a very gentle arch, not discernible in the profile, but traceable on topographic maps, on the other. The Santa Cruz Mountains are made up of a number of smaller regular blocks of all descriptions. The Santa Lucia Range not only shows this complexity, but the elevation of different parts has occurred at different times as well; but in most cases the application of the above principles of interpretation will indicate the various types of surface present, and thus show the relation of deformation to the development of the topography.

The irregular ranges are a more difficult problem. The southern part of the Diablo Range, east of the San Benito Valley, is of this type. The range can not be divided into definite blocks, nor is it a simple warp. In some parts true arches can be identified. These may border depressed regions or downwarps. High level valleys may be found at any elevation, giving little clue to the general baselevel at the time of their development. Yet even in such a complicated range as this many of the type features already discussed can be recognized, and by comparing them with similar features in a more regular range an idea may be gained concerning the origin and history of the whole.

PROCESSES PRODUCING SIMILAR RESULTS

Mention must be made of the processes which simulate the effects of tectonic activity, making it necessary to exercise the greatest care in interpreting the forms of the Coast Ranges. The chief one of these is differential erosion, which is accompanied by discordant conditions, such as temporary base levels at high altitudes, and which simulates topographic unconformities and scarps. The second is the variation in the rate of cycle development along large and small streams. A master stream may develop a considerable floodplain while the surrounding areas, drained by small streams, are still in a youthful stage. This gives the effect of discordance and might be interpreted as due to differential uplift.

Areas of Deposition

CLASSIFICATION

There are three general types into which the areas of active sedimentation in the Coast Ranges may be divided. The first is the depressed block, corresponding to the various types of uplifted blocks discussed in

the preceding section. The second is the irregular lowland found at the ends of ranges, in many cases covering considerable area. The third is the normal erosion valley, which, due to tectonic activity or climatic change, is being partially filled with sediment.

DEPRESSED BLOCKS

The northern section of the Salinas Valley is typical of the depressed blocks. Part of this valley is shown in figure 2 lying beneath its morning blanket of fog. It is fairly straight and is bounded by two prominent ranges. On one side is a fine fault-scarp, on the other rises the arch of the Gabilan Range. The floor of the valley may be divided physiographically into the alluvial fans from the ranges and the floodplain of the central stream, in this case the Salinas River. The sediments in these two parts show quite different characteristics. Another example is the Santa Clara Valley and San Francisco Bay. Here a marine facies must be added to the two alluvial facies.

The depressed blocks probably represent structural units, just as many of the ranges do. They are seldom perfectly regular, but their outlines are sharp and the faults along their sides can often be traced geologically.

IRREGULAR LOWLANDS

Some of the larger areas of deposition can not be explained simply as depressed blocks, even though they are subsiding. These are irregular areas crossing structural lines, bounding the ends of ranges, into which many of the larger faults extend and where they apparently terminate beneath the blanket of sediments. The San Benito Valley is a good example. San Pablo Bay represents such an area which has subsided below sealevel. The Los Angeles Basin is still another example. These may be areas of adjustment in which the horizontal components of movement on the great faults are taken up, as so many of these faults end in such areas.

The facies of deposition in these areas may be any of the three types mentioned above. The alluvial fans are usually not so pronounced. The chief difference is in the margins. Here they are irregular, alluviation often extending up the valleys and burying the ends of the spurs.

FILLED VALLEYS

The third type of area of deposition, the erosion valley filled with alluvial material, may be due to a variety of causes. The characteristic appearance of such a valley, especially the evenness of the valley floor and

the extension of the alluvium up the tributary valleys, burying the ends of the spurs, is shown in figures 10 and 11.

Tectonic movement is one process that may cause alluviation. It may do so in three different ways: First, the block on which the valley is developed may be tilted back, decreasing the grade and causing the stream to deposit wherever it previously flowed at grade. Examples of this sort have already been cited from the southern end of the Gabilan Range. Second, a barrier may be raised across the path of a stream by a fault. This has happened along the San Andreas Fault, on the east side of the Gabilan Range, causing the partial filling of young, steep-sided canyons,

FIGURE 10.—*Central Part of Peachtree Valley near King City*
A typical alluviated valley, due in this case to climatic change.

notably Cienega Valley. Third, a block may be uplifted at the head of a stream, causing overloading and therefore deposition farther down. If there is a plain at the foot of the scarp or uplift, an alluvial fan will develop, but if the stream enters a narrow valley the alluvium may be deposited down it for a considerable distance. An example of this kind is shown in figure 11. The uplift is along the San Andreas Fault. The scarp is better shown in figure 17.

The three types of filling due to tectonic activity are of particular interest, because they often furnish evidence as to the nature of the movement which has formed the range on which the valleys occur. Care must be taken, however, to eliminate the possibility of climatic change having effected the sedimentation.

In figure 12 two profiles are shown—one that of a mature stream in a moist climate, the other that in an arid climate. If the climate changes from moist to arid, it causes increased erosion at the head of the stream and deposition below, filling the valley. The theory is fully set forth by Huntington,[3] but the profiles shown here were drawn by the present writer without knowledge of Huntington's work.

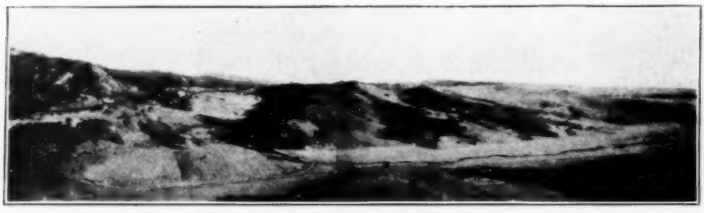


FIGURE 11.—*Upper End of Topo Valley near King City*
The alluvial floor is due to overloading by a recent uplift, shown on the left. There is no evidence of climatic change in the erosion of the surrounding hills.

Figure 13 shows rejuvenation in soft material producing bad-land erosion, thought to be due to such a climate change. In this particular case there has been no deposition because the master stream has not reached grade. In the case shown in figure 10, also thought to be due to climatic change, the bad lands are found above and deposition below.

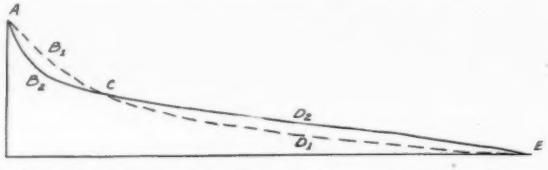


FIGURE 12.—*Stream Profiles under different climatic Conditions*
A, B_1, C, D_1, E represent that under moist conditions: A, B_2, C, D_2, E, that under arid conditions.

The chief criterion for distinguishing between valleys filled by tectonic activity and those filled by climatic change is their relation to direction. Tectonic activity acts as a rule only on valleys running in one direction, in a given block. Those running the opposite way may be rejuvenated. Climatic change affects all equally. It should be noted, though, that climatic change is much more effective in soft material than in resistant. This is probably the reason why its effects are found only locally, instead of everywhere, in the Coast Ranges.

[3] E. Huntington: The climatic factor. Carnegie Inst. Pub. No. 192, 1914, pp. 23-36.

It should be noted that, whatever the cause, filling will occur only where the stream was at grade or near it prior to the change of conditions. Where the stream is still cutting, it has reserve carrying power which will prevent alluviation. This explains many apparent anomalies, where streams have silted up only certain parts of their valleys.

In figures 10 and 11 small gullies are shown in the floors of the valleys. These are thought to be due to a recent change of climate from arid to moist, though they may represent merely the work of the streams between years of especially strong floods. They are a common feature throughout the Coast Ranges.

FIGURE 13.—*Bad Lands eroded in Gravels near Tres Pinos*
The rejuvenation is due to a climatic change from moist to arid.

TOPOGRAPHY OF ACTIVE FAULT-LINES

GENERAL STATEMENT

We have now considered the types of topographic surfaces found on the various blocks of the Coast Ranges. These blocks are defined and bounded by the great faults, such as the San Andreas, the Calaveras, the Haywards faults and many others. These are of especial interest, as many of them are either known earthquake faults or are potentially active. It was primarily to study these faults and locate the dangerous ones that the work leading to this paper was done. The results, in the opinion of the writer, show that physiography may be an important aid in the location of such fault-lines; that where a detailed geological study is impracticable the major faults may be located by this method, and that

in any case some idea of the recency of activity on a fault not otherwise known to be active may be obtained from physiographic study alone.

For the purposes of this paper, an active fault is defined as one on which topographic expression of movement on the fault has not been obliterated by erosion.

TYPES OF TOPOGRAPHIC EXPRESSION OF FAULTS

There are three ways in which active faulting may be expressed in the topography. The first is by rift features, the results of movement during a single earthquake or a series of earthquakes. The second is by the major topographic features, such as fault-scarps and fault valleys, produced by movements on the fault through a long period of time. The third is by erosional features due to differences in the character of the rock on the two sides of the fault or to the weakness of the shear zone.

FIGURE 14.—*Rift Scarp and Depression*

This occurs on the San Andreas Fault, in Bitterwater Valley, near King City. The scarp is about 15 feet high, in alluvial material.

RIFT FEATURES

The commonest types of rift features are the small scarp and the undrained hollow. A series of these may combine to make a continuous scarp or a continuous rift or ditch. To these must be added landslides, as these are much more prevalent along fault-lines than away from them.

All of these features are transient compared with the length of an erosion cycle, though they may be fairly persistent over periods of a century or more. Three examples are shown in figures 14, 15, and 16. The size of the trees growing on the scarp in figure 15 shows its age.

Rift features are found on all of the larger active faults, but only rarely on the smaller faults. On the San Andreas Fault the writer has seen them from Tomales Bay, north of San Francisco, south to the San Bernardino Mountains—a distance of 400 miles. A remarkable set of illustrations of these peculiar features is shown in the report of the California Earthquake Commission,[4] and reference should be made to this paper for further information concerning them.

Rift features, where they occur, may be taken as definite evidence of recent and potential activity along a fault-line. They can not be depended on, however, for locating all active faults, because, as stated above, few of the smaller faults show them. There are also many

FIGURE 15.—*Rift Scarp and Pond*

This is on the top of Mustang Ridge, near Priest Valley, on the line of the San Andreas Fault.

features that simulate them. Small ponds may be due to wind action. Scarps may be produced by local differential erosion. Landslides not only occur away from fault-lines, but simulate other features as well, producing ponds, scarps, and irregular surfaces. With practice, though, the characteristically discordant appearance of rift features is easily recognized, and there is not much danger of their being confused with the features enumerated above.

MAJOR TOPOGRAPHIC FEATURES

Fault-scarps.—The fault-scarp, on a large scale, is the most general evidence of active faulting found in the Coast Ranges. It is also, perhaps, the most difficult to analyze. The means for determining the char-

[4] Report of the California Earthquake Commission. Carnegie Inst. Pubs., 1908, vol. i.

acter of any scarp is the old topographic surface developed during the cycle preceding the one now active. As we are interested only in the latest movements on the faults in question, any vertical component of such movement must offset this surface, otherwise the displacement occurred too long ago to be of interest. The problem is to recognize such offsets. If the higher surface or surfaces can have preserved their character undissected through the time required to develop the topography of the surface in the lower area, there is no evidence of recent movement. If this is not the case, the fault-line must be considered as potentially active. This is the same problem of discordance of cycle development

FIGURE 16.—*Landslide*

This is near the San Andreas Fault, on the San Benito River. The slide is mostly in serpentine and is nearly a mile long.

already mentioned. To solve it, all the factors of resistance of material, structure, climate, and stream system must be considered.

Certain characteristics of the fault-scarps of the Coast Ranges may be mentioned. Many of them show triangular facets, but many others show a triangular arrangement of spurs with a completely dissected face. The profile may be concave, though this feature would be expected only on faults whose activity has ceased. The San Andreas scarp along the San Bernardino Mountains and the scarp of the Santa Lucia Range west of Salinas are examples showing these features.

The straightness of the scarps and of the fault-lines where they show no scarps is characteristic of the Coast Range region. This is one of the best criteria for distinguishing scarps due to faulting from similar features due to erosional processes.

The rapid cutting of a master stream is the chief agency which simulates fault-scarps. The sides of a valley so produced are often steep and may show fine triangular facets. There may be a well-preserved old surface above. The regularity of such a scarp is generally less than that of fault-scarps, however, and this criterion usually serves to distinguish the two. Erosion scarps are also plentiful, but these always are in strict accord with the structure and do not show the discordance of cycle development typical of fault-scarps.

FIGURE 17.—*Young fault-scarp*

This fault-scarp is along Little Rabbit Valley, on the San Andreas Fault (see figure 22). The material composing the hills in the foreground is fairly resistant sandstone and serpentine, that of the scarp is soft Pliocene sandstone and shale.

Fault valleys.—A peculiar type of valley is found in the Coast Ranges along the large earthquake faults. Such valleys have sides with convex profiles, though the slopes are gentle. They are the product of two arches, one on either side of the fault, formed without vertical displacement on the fault itself. A valley of this type is shown in figure 18. In this case the arch is only on one side, but it shows the depression along the fault, though there is no large stream flowing here, the drainage being across the fault-line to the left.

Another combination producing similar valleys is that of a scarp and an arch. The valley in which lie Crystal Springs and San Andreas Lakes is of this type.

The profiles of these valleys

do not resemble normal erosion profiles, and their width and straightness, even though they contain no large stream, are characteristic features. They often contain small hills, little horsts along the fault-line, which are very useful in mapping the active faults.

EROSIONAL FEATURES

Erosion scarps and erosion valleys may often be used in tracing the continuation of a known fault where it shows no truly active features. Most of the large faults of the Coast Ranges are shear zones of considerable width, so that even where the uplift has affected both sides a subsequent valley will develop along the fault. These valleys develop normal

FIGURE 18.—*Line of the San Andreas Fault east of Bitterwater Valley*
Note the smooth profile to the right and the mature topography on the left. The landslide in the foreground is typical of the fault-line.

profiles and should not be confused with the types described above. They are also much less dependable, as the fault-lines show a decided tendency to be found up the slope from the stream, to cut across spurs and generally to diverge from the line of the valley itself.

Erosion scarps on faults, sometimes called fault-line scarps, are the product of differential erosion on rocks of varying resistance brought in contact by faulting. They need not be discussed here.

VAGARIES OF ACTIVE FAULTS

It may be said in conclusion that active faults are notoriously inconsistent in their effect on the topography. Scarps develop facing either way along the same fault. They die out along the fault very suddenly.

There may be considerable distances, where the fault follows a stream valley or crosses an alluvial plain, where there is no sign of it in the topography. Figure 19 is a good example. This picture shows a section of the San Andreas Fault only a quarter of a mile to the left of that shown in figure 17, yet the only evidence of faulting is a hardly noticeable scarp, shown by the line at the right of the picture. Figure 20 is included to show the other extreme, the great rift of the Carrizo Plains, where the fault is marked by a prominent scarp and a ditch like a canal, extending across the plain as far as the eye can see.

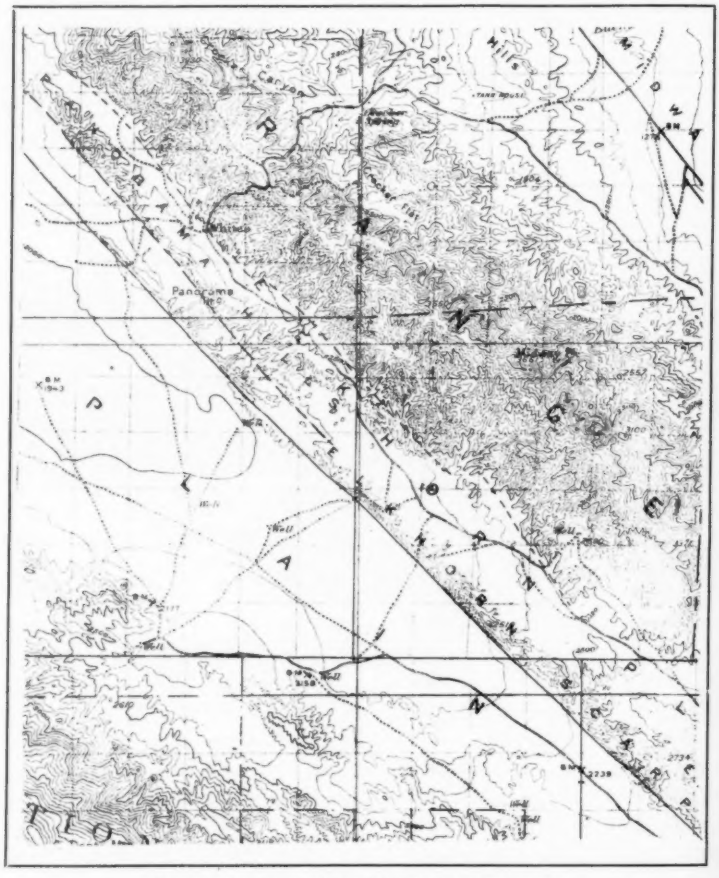
FIGURE 19.—*The Floor of Dry Lake Valley*
Showing the position of the San Andreas Fault.

STREAM TYPES AND STREAM SYSTEMS

Most of the streams of the Coast Ranges may be divided into two general classes: First, streams with consequent characteristics controlled by uplift; and, second, subsequent, obsequent, and resequent streams, adjusted to structure through differential erosion. These two classes are representative of the early and late stages of the cycle, respectively. Due to the varying degrees in which differential uplift and differential erosion control the topography, all gradations from purely consequent drainage to completely adjusted drainage are found. In addition, because of the rapidity with which one erosion cycle follows another before the older passes much beyond the stage of maturity, gradations in the other direction are found, the subsequent drainage of the earlier cycle persisting long after renewed uplift and only gradually being conquered and replaced by the new system with consequent characteristics. There is, therefore, a perpetual contest between the two types of drainage, and because of the lag after inauguration of a new cycle a given drainage

system or even a given stream may show characteristics of both types and the combinations may be quite complicated.

The consequent streams of the Coast Ranges may be divided into two types—the longitudinal consequents and the lateral consequents. The


Panorama
Hills
Panorama Hills
Cuyama Valley
Cuyama Fault
Mirage
Lake
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ing or displacement of the topographic surface. The lateral consequents flow down tectonic slopes (as differentiated from erosion slopes) either on tilted blocks, on the sides of arches, or on fault-scarps. The longitudinal streams are the master streams in such a system.

As the cycle advances and the streams begin to adjust themselves to the underlying structure, they seek out two types of lines of weakness. Of course, they develop along soft beds where the structure is that of inclined sedimentary rocks, but the principal lines are again the fault-lines. The faults of the Coast Ranges generally have fairly wide shear zones, so that even where the fault-line is not a tectonic valley it is very apt to become the location of a master subsequent stream.

Not all the streams of the Coast Ranges can be classified as consequent and subsequent. Much of the region is underlain by massive rocks in which structural control is slight. Mountain blocks of this kind are drained by an irregular pattern, provided there has been no tilting, and the streams must be classed as insequent. There will be little change in such a drainage system from one cycle to another, except near the borders of uplifted blocks or where the direction of slope is changed during uplift.

Antecedent streams also can not be classified with the main groups, and there are many of them in the Coast Ranges. The Golden Gate is probably the submerged valley of a true antecedent stream. There are, however, two other types of transverse streams flowing across a mountain barrier which may be confused with antecedent streams. The first is the lateral consequent which has cut back across a ridge to capture a sluggish longitudinal stream which has been lifted above the level of the consequent drainage by tilting or unsymmetrical warping. A good example of this is found just back of Stanford University, where a stream draining to the bay has captured a section of the valley along the San Andreas Fault.

The second distinct type of transverse stream is the stream formed by the overflow of a tectonic lake. Such lakes may be formed along fault-lines, and if the drainage down the fault-line itself is obstructed by the longitudinal warping of the blocks it will overflow at the lowest point on the bounding ridge. This point may be the channel of an old stream, but this is not necessary. Such a stream can not, therefore, be classed as antecedent, and as it grows from its head downward it is not the same as a consequent that works back to capture the longitudinal drainage. An example of this type of stream is found in San Mateo Creek, which drains part of the line of the San Andreas Fault, including Crystal Springs Lakes.

The writer knows of no important example of a superimposed stream in the Coast Ranges, though such very likely exist.

Due to the rapidly changing conditions of drainage, there are many examples of stream capture. Any topographic sheet will show several. This results in sudden changes in the rate of stream development at certain points in a mountain mass and causes confusion when the physiographic history is studied on the basis of topographic unconformities and the stages of the erosion cycles.

This brief statement of drainage conditions in the Coast Ranges will serve to show that there are probably few regions offering the variety of types and the complexity of systems found here.

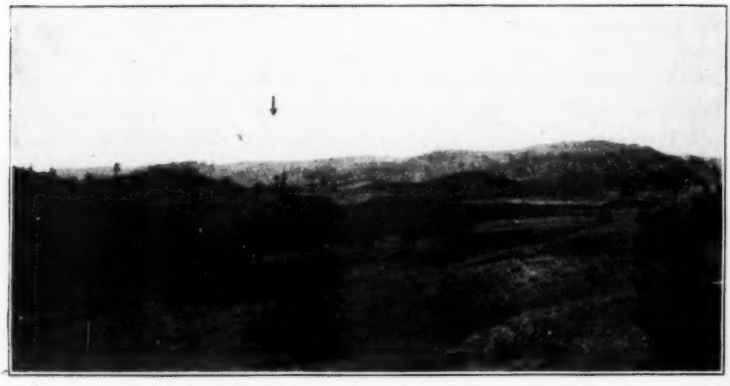

FIGURE 21.—*Rejuvenation resulting from Stream Capture*
The head of Peachtree Valley diverted by Slack Creek, looking west. The arrow shows the point of capture from the southwest.

PHYSIOGRAPHIC CORRELATION

PRINCIPLES

In studying a region of active faulting like the Coast Ranges, the physiographer finds on each block two or more surfaces developed during different cycles of erosion and showing definite characteristics over that block. The surfaces on adjacent blocks, however, may not show quite the same characteristics. It becomes necessary, therefore, to find some means of correlation between the different blocks in order to interpret the physiographic history of the region as a whole.

In many regions of uniform uplift two criteria may be used to correlate physiographic surfaces. The first is continuity and position in the profile. One cycle may be represented by accordance of summits; an-

other may show areas of flat surface a certain distance below the summits or above the general drainage level. The other criterion is the distribution and age of the sediments found on the surface or its extension. The Cretaceous and Tertiary peneplains of New Jersey are examples.

Neither of these two criteria can be used in the Coast Ranges. Continuity and position in the profile fails because of differential uplift. Sediments can not be used except in rare instances, partly because the uplifted blocks rarely are covered by them and partly because all of the cycles are so recent that it would be impossible to make the distinction between sediments corresponding to them in age.

The physiographer is forced, therefore, to fall back on two criteria in which the margin of error may be considerable. The first is an estimate of the probable elapsed time since the conditions under which an erosion surface developed were changed. The second is the probability of any movement affecting a large region acting more or less simultaneously throughout. If an upland surface has been dissected to a certain stage and the dissection of a surface in an adjoining area is believed to have taken about the same length of time, when all the factors of rock hardness, stream distribution, amount of uplift, and climate have been taken into consideration, then the two surfaces may be tentatively correlated on the assumption that the deforming force acted on both blocks at approximately the same time, causing simultaneous uplift.

These are admittedly criteria involving to a large extent the personal factor, and the question may be asked whether it is even worth while attempting to correlate surfaces under such conditions. In the field, however, certain types of surface are so widely distributed, especially in the regular ranges, and the degree of dissection corresponds so well to the controlling factors of rock hardness, stream spacing, and amount of uplift that it seems plausible to assume that these may be correlated, giving us an approximation of the general history of the region.

In a region of active faulting no tectonic movement is a continuous one; it is made up of a number of small movements. It therefore becomes necessary to define what is meant by a cycle of erosion. The theoretical cycle is the period from the beginning of an uplift until the time when the erosive processes can no longer act on the mass. Nowhere is the work of such a cycle carried to completion, and in the Coast Ranges this is even more true than in most regions, few surfaces developing on the higher and more resistant blocks beyond maturity. We are dealing, therefore, with partial cycles, and this is what is meant when the term cycle is used.

The history of the Coast Ranges indicates that an orogenic epoch may

be subdivided into smaller stages, each of which affects a wide area, but shows definite characteristics and is divided from the others by periods of quiescence. The characteristics of such a period and the time elapsing after it permit the development of an erosion surface on the uplifted blocks that will show distinctive features and will be marked off by topographic unconformities from those surfaces developed in other periods. Such a surface represents the result of a partial erosion cycle.

The movement in these periods of deformation, however, is not continuous, but is a series of minor movements. The number of these is large. They may be represented, for instance, by individual earthquakes. Any one which causes uplift and renewal of stream cutting might be considered as initiating a new cycle, but as it tends in the same direction, produces the same effect on the surface, and is soon absorbed by the general development of the surface, it is not worth while trying to distinguish it from the general movement. In some cases, however, the effects of these minor movements can be seen locally. They may serve, therefore, to delimit minor divisions of physiographic time, which may be called episodes within the major cycles.

To recapitulate, movements or series of movements which are of long enough duration and great enough extent to influence the topography of a whole block or series of blocks are considered as delimiting cycles; minor movements, which affect local areas, may be used to subdivide cycles into episodes.

Other events besides the minor orogenic movements may be used to subdivide the cycles. The two principal types in the Coast Ranges are stream capture and climatic change. They modify the development of the cycle, each one producing local breaks in the erosion surface similar to topographic unconformities, but neither changing the baselevel of the cycle.

In the recent cycle in the Gabilan Range four episodes, marked off by minor movements, stream captures and climatic change, can be distinguished.

There are two phases in the work of the erosion cycle which develop, according to conditions, somewhat independently of each other. One is the development of the stream valleys, the other the dissection of the landmass. The first depends for its rate of progress on the hardness of the material, the amount of uplift, and the size of the individual stream. The second depends on the first two factors and on the spacing and size of the streams. Both are also controlled to a certain extent by climate.

In judging of the time elapsed since an old topographic surface was developed and uplifted, it is the amount of dissection of the mass that

must be considered. This phase of erosion considers the block as a whole; it eliminates the conditions brought about by local movement and other accidents, and gives the best clue to correlation of the major cycles between different blocks.

The development of the streams and valleys, however, is very sensitive to the least movement. A small change in elevation will cause graded streams to deepen their channels or deposit sediment. Stream capture also produces local rejuvenation along both the capturing and captured stream and leaves a high valley out of accord with the general drainage. Climatic change likewise shows its effects in the stream valleys. It is to the character of these valleys, therefore, that we must look for the minor details or episodes of the history of each block. Sometimes such episodes can be correlated with those in other blocks, especially those marked off by climatic change, but the other types are entirely local in most cases.

PHYSIOGRAPHIC HISTORY OF THE GABILAN REGION

General statement.—The following brief account of the physiographic history of the Gabilan region is included to illustrate the application of the above principles of correlation and to give an idea of the extremely recent age of the physiographic features of the Coast Ranges.

This region lies about 150 miles south of San Francisco, near the coast. It includes the Gabilan Range, its northern extension east of Monterey Bay, the San Benito Valley, with its included groups of low hills, and the rift zone of the San Andreas Fault, with a portion of the Diablo Range east of these.

Topography and geology.—The region may be divided into four parts, on the basis of geology and physiographic history. These are the Gabilan Range, the San Benito Valley, the rift zone, and the Diablo Range. The Gabilan Range is separated from the San Benito Valley by the San Andreas Fault, the eastern slope of the range being the dissected fault-scarp. Southeast of the San Benito Valley there is a series of faults paralleling the San Andreas, forming a distinct unit, called the rift zone because of its structure. The Diablo Range rises to the east of the valley and the rift zone.

The Gabilan Range is a single great fault-block, made up of the Santa Lucia complex and the granite which intrudes it. The granite forms the greater part of the range. In the southern part there is an extensive series of lava-flows, the thickest and most resistant portion forming the prominent peaks of the Pinnacles and Chalone Mountain. North of Gabilan Peak the range breaks off to lower levels and is underlain by Tertiary sediments and lava-flows. South of Chalone Mountain there

is a region of low hills developed in soft Miocene and Pliocene sediments. The San Benito Valley is a large alluvial flat, a lowland of the irregular type, into which many faults seem to pass and die out. There are several groups of low hills within the boundaries of the basin. The more important are the Lomerias Muertas, in the northwestern part, and the Bird Creek Hills, the foothills of the Gabilan Range, east of the fault. These hills are underlain by Pliocene or Pleistocene gravels, which have been closely folded before the beginning of the physiographic history shown in their surface. This is of considerable importance in connection with the age of the peneplain recognizable on the softer beds throughout this region.

The rift zone is, topographically, a series of ridges and valleys running parallel to the San Andreas Fault, underlain at the northern end by the same gravels found in the hills of the San Benito Basin, and farther south by alternating strips of Tertiary (Miocene and lower Pliocene) sandstones, and serpentine, supposedly of Jurassic age, bounded by the faults mentioned above.

The eastern margin of the rift zone is rather indefinite, the ridges swinging off to the southeast to the main Diablo Range, and older rocks, Cretaceous sandstones and the Franciscan complex (Jurassic ?), cropping out from beneath the gravels or appearing on the eastern side of faults. The boundary of the Diablo Range is much less definite than that of the Gabilan Range, its altitude shows more variation, and its geology is much more complex.

Erosion cycles.—The Gabilan Range offers the most definite series of topographic surfaces to be found in any part of this region. In this range there is definite evidence of two cycles and some less definite evidence of an older one.

The present relief of the range is upward of 3,000 feet, the elevation ranging from 200 feet on the west side, in the Salinas Valley, to 3,400 feet at Mount Johnson. The relief on the east side is less, the valley of the San Benito River lying at about 700 feet. The range is dissected by steep-sided, narrow canyons, few of which have reached grade; but if one goes up these canyons on the east slope, one comes out at their heads into broad, open valleys, with rounded slopes and mature characteristics, at an elevation ranging from 1,900 to 2,500 feet. The relief above these valleys is between 800 and 1,500 feet, but the topography is not rugged.

The steep canyons cutting down to the present baselevel represent the latest cycle. The mature high-level valleys represent a preceding cycle which developed to maturity during a period of quiescence, when the range stood nearly 2,000 feet lower than at present.

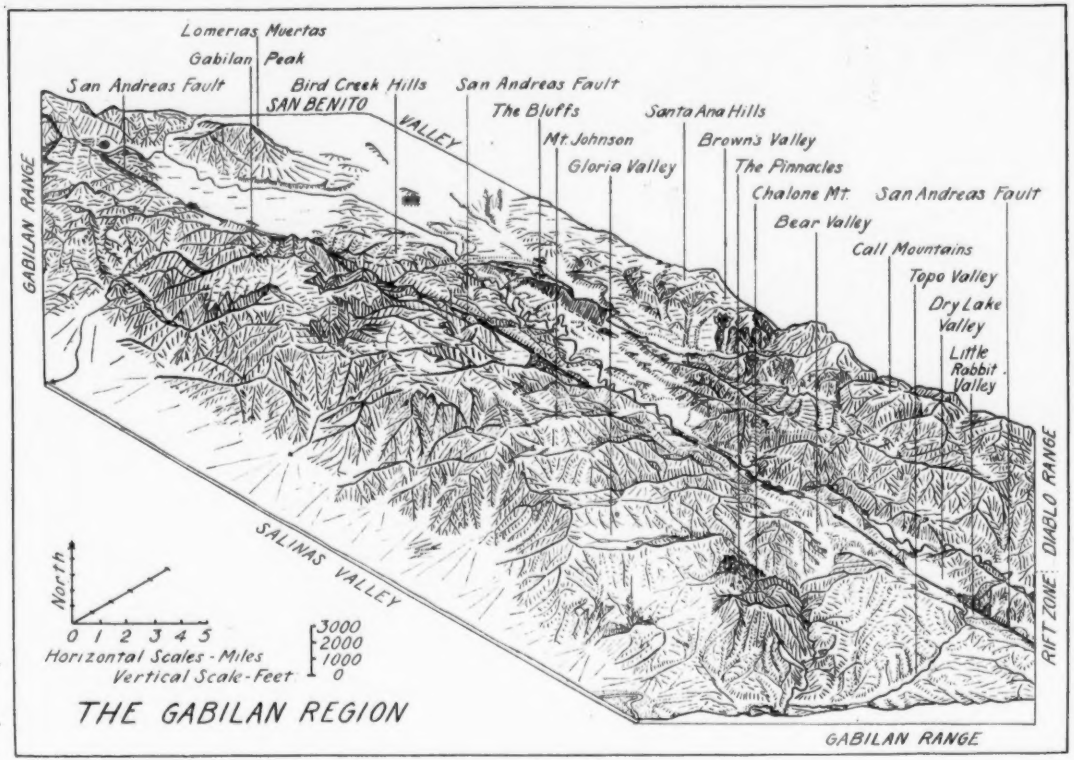

FIGURE 22.—*Isometric Diagram of the Gabilan Region*

On the tops of the highest peaks, particularly on the summit of Mount Johnson, there is a flat surface apparently divided from the slopes of the high-level valleys by a topographic unconformity. Mount Johnson shows a very even profile across the range. This upper surface is believed to represent a cycle older than that of the high valleys. The chief reason for this assumption is that the visible processes are dissecting this surface and destroying its uniformity, even though the young canyons of the latest cycle have not cut back this far, and the processes of the intermediate cycle are proceeding in their normal course on the slopes below the supposed surface.

This oldest surface is designated, for convenience, the first cycle, as it is the oldest found in the region under consideration. The high-level valleys belong, therefore, to a second cycle, and the recent cycle may be called the third cycle.

North of Gabilan Peak the range is warped down to the northwest. This warping has caused increased erosion in the recent cycle, so that little, if any, of the second cycle surface is left. But still farther north the range maintains its altitude at about 1,000 feet, and here, in the Tertiary sediments, which are in general less resistant than the granite of the main range, there are not only old valleys, but wide flats, the relief above them being less than that above the high valleys of the granite area. West of this area there is a wide stretch of low hills extending to the ocean. These are made up of soft Pliocene or Pleistocene sands, and their supper surface, which grades into the old valleys of the range, is very uniform and suggests a peneplain, though it is now well dissected.

It appears, therefore, that throughout the block of the Gabilan Range the second and third cycles can be definitely traced and correlated.

Turning to the San Benito Valley we find two main cycles. The valley itself shows only one, the latest, but the hills rising out of it show young gullies and canyons cutting into a late mature topography which grades into a true plain near the present course of the San Benito River. The Lomerias Muertas are surrounded by such a plain, a very uniform surface which has been arched slightly to give them added relief. The Bird Creek Hills show a rolling upland cut by young canyons, as shown in figure 3. Across the river there is an extensive area, above the present stream level, yet with a nearly level surface. This has been faulted up in one place in a horst forming the top of the plateau shown in figure 4. This plain has been given the name of the Tres Pinos peneplain.

The interesting feature of the physiography of this region is the relation of this peneplain to the sedimentary series underlying the region. In the rift zone the youngest rocks carrying marine fossils belong to the

Etchegoin or middle Pliocene series. These beds are thoroughly consolidated sandstones and shales. Above them, apparently unconformably, is the series of gravels already mentioned as underlying most of the San Benito Valley. This series is called the San Benito formation. It is made up of interbedded gravel, sand, and clay, and in general is only loosely consolidated. The very recent terrace gravels along the river can hardly be distinguished from it except by the structure. As this series is so much softer than the middle Pliocene series, it does not seem reasonable that it can be older than upper Pliocene, and it may very well be Pleistocene. Yet these beds have undergone folding which has left them closely compressed and in some cases even overturned. This folding is the post-Pliocene deformation described by Lawson.[5]

FIGURE 23.—*Fold in the unconsolidated San Benito Gravels west of the Bluffs*

The Tres Pinos peneplain has been cut across the tops of these folds. It must, therefore, be younger than the Pliocene, and it and all later erosion surfaces must have developed during Quaternary time.

The next step is to correlate, if possible, the cycles of the San Benito Valley with those of the Gabilan Range. To do this we must apply the principles already outlined, working back from the most recent as far as there seems to be any reasonable basis for correlation. The first question, therefore, is whether the latest cycle in each region corresponds approximately in length to that in the other.

In the San Benito Valley the underlying rocks are soft and easily eroded. In the Gabilan Range they are much more resistant, though not

[5] A. C. Lawson: Post-Pliocene deformation of the coast of southern California. Univ. Cal. Pubs., Bull. Dept. of Geol., vol. 1, 1893, p. 115.

extremely so. The Gabilan Range has between 2,000 and 3,000 feet relief, against a maximum of 1,000 feet in the valley region. The Gabilan Range is drained by comparatively short streams, as compared with the San Benito River, which flows through the valley, but the minor streams of the valley are shorter than those of the range.

The first factor points to much more rapid cycle development in the valley than in the range. The second factor, that of relief, tends to increase the speed of dissection of the range, but slows down the valley or stream cycle. The factor of size of streams would point to more regular development in the range, and to a wide floodplain along the master stream, with little dissection of the surrounding hills in the valley region. With the extreme difference in the resistance of the rock of the two regions, the author's estimate is that, aside from the valley of the river itself, the lower area should show a slightly more advanced stage in the cycle than the Gabilan Range. This is the case in most sections. The Bird Creek Hills show an adolescent topography in the latest cycle, while the range is still in a youthful stage. The Lomerias Muertas, however, show an earlier stage than the Bird Creek Hills, which suggests that they have been uplifted later. The plateau shown in figure 4, called the Bluffs, is even less dissected and is certainly much later in origin than the Bird Creek Hills; but the latter are the closest to the Gabilan Range, and the Tres Pinos surface is found on their summits. At one point the high-level valleys of the second cycle in the Gabilan Range appear to be warped down on the east to the fault-line. Where this has taken place they correspond in elevation with the remains of the valleys on the Bird Creek Hills. Considering the structural weakness of the material underlying the hills, it seems unlikely that a movement which raised the Gabilan Range nearly 2,000 feet would not have affected these hills just across the big fault. All these factors, therefore, point to the probable correlation of the uplift which ended the second cycle in the Gabilan Range with that which ended the Tres Pinos cycle in the San Benito Valley.

There are other reasons for this correlation. The peneplain on the soft rocks northwest of the Gabilan Range, which merges into the old topography of the upper surface of the Tertiary rocks in the northern part of the range, is very similar to the Tres Pinos peneplain in its characteristics and in the degree of dissection reached since the latest uplift. The correlation of this surface with the high-level valleys of the main range to the south seems to be entirely reasonable, as the two are in the same block and are apparently continuous.

Similar relations may be seen in other ranges in this general region. The Santa Lucia Range west of Salinas comes down at its northern end to a lower level, and the upper surface changes from a mature topography at high levels, cut into by young canyons, to a series of flat-topped hills in soft sediments, dissected in the present cycle to a more advanced stage than the main range.

The next step in the correlation is to determine the relation between the beginning of the second cycle in the Gabilan Range and that of the Tres Pinos cycle in the San Benito Valley. The same factors of resistance of material, amount of uplift, and size of streams must be considered.

A much longer time must have elapsed between the beginning and the end of the second cycle in the range than since its close. Nevertheless, the region was left with a relief of over 1,000 feet, and an occasional remnant of the previous cycle is still preserved. In the valley region an extensive peneplain was developed, but this was aided by the size of the stream flowing through the region. Judging from the size of the flood-plain of the same stream today, cut since a late stage in the latest cycle, the Tres Pinos plain could easily have been cut while the mature surface was developing on the range. A better comparison can be made where the Tres Pinos surface is represented by low hills, as in the Bird Creek Hills. Above the topographic unconformity shown in figure 4 the topography is that of late maturity. This is the stage to be expected in soft material with moderate uplift to correspond to the early maturity of the granite region.

A parallel may be drawn with the Tertiary cycle in New Jersey. The highlands of gneiss still preserved remnants of the Cretaceous surface, while a peneplain with moderate relief and smooth rounded features was developed at a lower level on the softer Triassic sediments. It is reasonable, therefore, to correlate in a general way the beginning of the cycles of these two surfaces. This gives us an approximate date for the uplift inaugurating the second cycle in the Gabilan Range, for we know that the uplift before the Tres Pinos peneplain is not older than the end of the Pliocene and may be much younger. As this surface is the oldest known in the valley, it is impossible to say how many cycles occurred between the folding of the San Benito gravels and the beginning of the Tres Pinos cycle, but it seems unlikely that there were more than one, owing to the shortness of the time, and this cycle may have been the one inaugurated by the folding.

The beginning of the second cycle was the end of the first. There is

no evidence concerning the length of time which elapsed during the earlier cycle. In the Salinas Valley and on the southern end of the Gabilan Range, there is a continental formation known as the Paso Robles, which has been assigned to late Pliocene or early Pleistocene time. A careful study might show the first cycle surface either dipping under or grading into these gravels. The relation between the two has not been worked out.

The rift zone shows the same two cycles that appear in the San Benito Valley. The older of the two has been faulted and is found at different levels in the different blocks. Along the main course of the San Benito River, in the westernmost block, there is a considerable area which appears to have been downfaulted to the present level of the river. Between this and the next preserved remnant to the east is a fault-scarp which increases in height toward the south until there is a difference in level of the two areas of surface of over 1,000 feet. The depressed block is of importance in connection with the history of the San Benito River, which used to flow across the Gabilan Range south of Chalone Mountain, and which was diverted to the north by the elevation of the range and the subsidence or inaction of the block on which it now flows. There was probably a considerable lake formed on this block before reversal was complete, the eastern boundary being made by the scarp just mentioned, the western by the scarp of the San Andreas fault, the main slope of the Gabilan Range.

In the rift zone and in the San Benito Valley there are minor incidents which may be used to subdivide the recent cycle. These are the minor movements producing local effects and the accidents, stream capture and climatic change. Five divisions of the cycle may be recognized. The first episode, of course, is the beginning of the cycle itself. This is shown by the rejuvenation of the Gabilan Range, and, in the regions just mentioned, by the uplift of the Bird Creek Hills and most of the rift zone.

On the east side of the Gabilan Range, near its southern end, there is a valley of mature aspect, developed in the soft Paso Robles gravels below the general level of the second cycle valleys. It is known as Bear Valley (see figure 22). It must belong to the recent cycle because of its position, but there is no stream in it now which could have cut it since this cycle was inaugurated. This is the old course of the San Benito River across the range. The present valley of the river cuts directly past the head of Bear Valley, and just north of this point is the depressed block already mentioned. The capture of the river at this point marks the

start of the second division of the recent cycle. It could not have occurred at the beginning of the cycle, because a considerable time elapsed after uplift began during which Bear Valley was cut; yet the region along the river above the point of capture is nearly as far advanced in the cycle as the main Gabilan Range, taking into account the difference in structure and hardness.

The fact that the group of hills in the San Benito Valley known as the Lomerias Muertas appears to have been uplifted later than the Bird Creek Hills has already been mentioned. The degree of dissection here corresponds to that along the San Benito River above the point of capture; hence the uplift of the Lomerias Muertas is correlated with the second division of the recent cycle. We have, therefore, the approximate correlation of the accident of stream capture in one part of the region with a minor orogenic movement in another.

The third stage of the cycle is likewise marked both by an accident and a minor movement. The young fault-scarp shown in figure 17 is certainly of later origin than the Lomerias Muertas. The plateau shown in figure 4, known as the Bluffs (for location see figure 22), corresponds in degree of development to this scarp. Both are in soft material, yet neither has been much dissected. They are both due to minor uplifts along faults.

Looking at figure 13, we see gullies in similar material, of similar size and character to those developed on the scarp and on the west face of the Bluffs, but due to a different cause. As has been explained, in this case they are thought to be due to climatic change. The writer has seen many other cases of this type of erosion, showing that the change was fairly widespread. In general they appear much younger than the dissection of the Lomerias Muertas, yet not as young as some quite recent features which are referred to a fourth stage. They are therefore correlated with the uplift of the Bluffs and of the Little Rabbit fault-scarp. This permits us to correlate another feature which can not be compared on the basis of stage in the cycle, namely, the filling of the valleys where this is due to climatic change. As there is evidence only of the one change, the filling and the gullying must have taken place at the same time; hence the filling also belongs to the third division of the recent cycle.

The Bluffs have been uplifted in more than one movement, as is shown by one well marked and continuous set of terraces. There are six levels of terraces on the west slope, but the minor ones are thought to be due to normal migration of meanders during slow uplift rather than six short

uplifts with periods of quiescence between. Only the one mentioned is considered as marking a pause in the uplift. This must be later than the original uplift, and therefore marks a fourth episode in the cycle. Another event put in this stage is the capture at the head of Peachtree Valley, the effect of which is shown in figure 21.

A fifth and final division is shown in extremely recent gullying of the alluvial floors of many valleys. Such gullies are shown in figure 11. They are almost universal throughout the Coast Ranges and occur regardless of direction. They are supposed to be due either to a climatic change or to cultivation. They are small enough to have been developed within historic time.

This series of events in the Gabilan Range and the adjoining regions gives us a scale of physiographic time for the region in general which we believe to be correct as to sequence, even though it gives only a vague notion of comparative lengths of cycles and episodes. In the Diablo Range no such definite sequence can be worked out. In general, two erosion cycles are recognizable, but they are not continuous either in elevation or stage of development. At Browns Valley, for instance, just south of the San Benito Valley, there is a high-level valley as perfect as those in the Gabilan Range. To the north of it the surface may be traced for a short way, but seems to run out on a spur and be carried below the level of the valley by a pitching arch in the Santa Ana Hills. East of the rift zone is a minor division of the range, known as the Call Mountains, which carries on its crest a well preserved erosion surface, slightly arched, which is nearly a peneplain. The degree of dissection of this arch suggests that it was formed about the time of the beginning of the third cycle in the Gabilan Range. The uplift around Browns Valley was probably later, say about the second episode of the third cycle; yet back of these regions, in the main range, the stage reached in the present cycle is more advanced than anything found in either the Gabilan Range or the San Benito Valley since the second cycle. All that can be done, therefore, is to try to recognize individual features, like the arch of the Call Mountains, and to correlate these as nearly as possible on the basis of the scale worked out in regions with a more systematic history.

Summary

The California Coast Ranges are tectonic mountains in which the major features are controlled by differential uplift, and the minor features by this agency combined with differential erosion.

Three types of surface may be produced by differential uplift, each best recognized by one of the three characteristics of topographic unconformity, stream system, or profile. They are those uplifted without being deformed, characterized by a sharp and regular topographic unconformity between the old surface and the new cycle; tilted surfaces, characterized by a consequent drainage system or the tendency to develop such a system; and arched surfaces, characterized by a smooth convex profile not duplicated by other processes. These three types, combined with fault-scarps, are found in various combinations making up the individual units of the Coast Ranges.

There are also three types of areas of deposition: simple depressed blocks, irregular areas under which the faults die out, and valleys which have been filled as a result either of some type of differential uplift or of climatic change.

The characteristics of active fault-lines are considered, including rift features, scarps, valleys due to deformation of the surface, and valleys due to erosion. The California earthquake faults are noted for the inconsistency of their topographic expression.

The streams of the Coast Ranges offer a wide variety of types. In general they fall under the main headings of consequent and adjusted streams, or they are streams persisting from a previous cycle, but showing the characteristics of one of these types, relative to the new uplift. There is a perpetual contest between the two for supremacy, accentuated in this region by the rapidly repeated uplifts. Stream capture is therefore very common.

Correlation of physiographic surfaces in such a region can only be done by estimating the elapsed time of each cycle on each block, beginning with the latest and working backward, and comparing the results for different blocks to gain an idea of the history of the whole. For convenience, a cycle or, strictly, a partial cycle is defined as the time between uplifts which affect a whole region, measured by the development of the topographic surface, while the effects of minor local movements and of accidents, such as stream capture and climatic change, are used to delimit the subdivisions of the major cycles.

When these principles of correlation are applied to the region around the Gabilan Range, we find that the work of two cycles can be recognized over most of the area, both of these having had their full development since the end of Pliocene time. The effect of a still earlier cycle can be recognized in the region of hardest rock, and the latest cycle can be split into five divisions, marked off by stream captures, climatic changes, and

minor orogenic movements. In the case of the Diablo Range, however, the history has not been uniform, and we can only estimate the age of certain features or surfaces by comparing them with those surfaces assigned to cycles in the more systematic region.

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PRIMARY STRUCTURE OF GRANITE MASSIVES[1]

BY ROBERT BALK

(Presented in abstract before the Society December 31, 1924)

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INTRODUCTION[2]

Large parts of the German Highlands are made up of folded Paleozoic and crystalline rocks, forming the Variscian Mountains of Suess. Except for their shorter length, these old ranges surprisingly resemble the Appalachian Mountains, both in their material and in their structural behavior. Latest of all the rocks, as in New England and the southern Appalachians, there appears in the core of the German mountains a large number of granitic rocks. While they were once generally supposed to be large batholithic, bottomless masses, that had risen upward by magmatic stoping, which cut the folded sedimentary strata unconformably and which were more or less independent of the associated country rock, it has lately been shown by Professor Hans Cloos, of the University of

[1] Manuscript received by the Secretary of the Society September 8, 1925.

[2] The writer is indebted to Professors James F. Kemp and Charles P. Berkey for having kindly asked him to present a paper on the subject before the meeting of this Society at Ithaca on the 31st of December, 1924. The topic deals with various problems and questions, many of which are still open. Professor Cloos' methods, discussed in this paper, and which are set forth in a large and rapidly increasing number of contributions, are not to be understood easily from a single, brief summary. The writer, who studied under Doctor Cloos, would be glad, therefore, if the reader would bear in mind this difficulty. He plans to publish a more detailed paper on several New England granites which will furnish further information.

Breslau, Germany, and his associates that at least some of the granites have a different history. We know now that their material, while rising, was affected by tectonic forces; that their origin and present location were influenced by movements and zones of weakness of the country rocks, and that they do not all continue to considerable depths like batholiths. We are now able to describe and to check their development step by step, and we can identify different subsequent stages. We have learned that after the earliest stage, when forerunners of an intrusion entered the crust, the magma increased in mass, rose, and augmented its size and dynamic power. The magma has been affected, nevertheless, by mountain-making forces; has finally crystallized, and has consolidated, forming a hard, brittle rock which still preserves evidence of magmatic processes. The last structures imposed on the mass are those produced by tectonic stresses.

The research work done in the last six years has made new contributions to the problem of the differentiation of magmas and has revealed also important relations between magmatic and tectonic movements. As the methods which have led to the new results, and which have been worked out by Professor Cloos, are of general interest, the writer considers it useful to present a brief report on them, the more so as he has tested in 1924 the applicability of the methods in parts of the United States. Later, there may be taken up the question of the continuation in depth—a subject on which light is thrown by these methods. Finally, some economic questions may be mentioned regarding the location, direction, and continuation of some magmatic ore-bodies and the possibility of finding mineral deposits under igneous bodies.

The primary Structure

The German geologists divide granitic rocks into two groups:

1. *Gneissoid granites* ("Gneisgranit," "Orthogneis," "Eruptivgneis") exhibiting a platy structure, which, however, may be so slightly developed that the rock practically is a massive one. The contact lines are conformable to the strike of the country rock (concordant), representing especially *lit-par-lit* injections. Most of them appear as elongated masses parallel to the regional trend. Inclusions which generally lie with the largest axis parallel to the foliation plane are often assimilated in greater or less degree and present contacts lacking sharpness of definition. Cross-cutting contact lines, both on inclusions and the wall rock, are rare exceptions. The majority of gneissic granites exhibit phenomena of folding.

2. *Granites proper.* Massive rocks, generally without platy foliation, with sharp, unconformable (discordant) contact lines. Local *lit-par-lit* injections are very seldom observed. The ground plans of the massives are often circular, without visible relations to the structure of the wall rock. Inclusions show angular contours and do not exhibit assimilation. Phenomena of folding are missing.

The foregoing definitions have been given to avoid misunderstandings. Regarding the interpretations of the differences between the two varieties of granite, see number 4 in the bibliography at the close of this paper. In Germany there seems to be no gradation between these two types. Most of the gneissoid granites are older than the massive granites, but they also probably differ among themselves in age. In the following pages we have to do merely with rocks of the second group.

Field-work in the extensive granite quarries of Strehlen, Silesia, revealed the surprising fact that in granites of the second, or massive, type there is also a parallel structure. On flat-lying structural planes as well as on east-west vertical planes the minerals appear slightly elongated in an east-westward direction (figure 1). The feldspar crystals point in one direction, quartz grains appear as small, elongated ellipsoids, and a good many of the mica flakes exhibit a parallel arrangement. On steep north-and-south planes, however, this structure is missing. On these, only, the granite is virtually a massive rock, and any platy structure, like a foliation, is missing, the granite thus representing only a *linear* parallelism, just like the grain in a tree trunk. The whole rock exhibits a very characteristic structure.

So far as yet studied, not many granites show the "stretching" (German "Streckung") as well as the Strehlen granite. Sometimes specially careful attention is necessary to recognize the structure in the field. It is so elusive that thin-sections generally fail to show it, even in well stretched rocks. Long ago the experience of the quarrymen has shown that granite splits most easily parallel to this structure ("rift," "grain," German "Reisseite," "Stehgang") and with difficulty at right angles to it ("hard-way," "cut-off," German "Unspalte," "Kopf"). The steep rift-planes, therefore, strike parallel to the linear parallelism; the hard-way crosses it at a right angle. The ease of the rift parting is merely due to original, minute planes of weakness in the rock, which are due to parallel boundaries between the minerals (compare T. N. Dale, 17, page 18). The two vertical parting planes join a third one, the flat-lying "lift" (German "Lager," "Hebgang"), to furnish the natural rectangular blocks of any granite quarry.

What is the origin of this linear parallelism? Is it a primary flow

structure, an early record of fluid magmatic movements, or a later, secondary phenomenon, connected with orogenic pressure, related to cataclastic structures?

The studies of Cloos and his assistants showed that most of the inclusions point with their longest axes nearly or quite parallel to the strike of the stretching.[3] The numerous slight flow-bands, "Schlieren," light or dark shades and waves in the granite, follow the same direction.

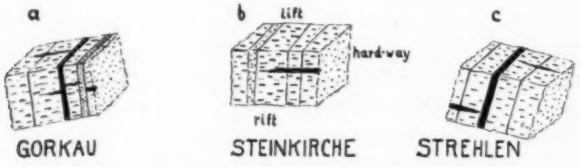

FIGURE 1.—*Three paving Blocks*

Showing the mutual coordination of the stretching, flow-bands, crossing joints, and dikes, and also the arrangement of the three technical parting planes. The "lift" lies horizontal (1*b*) or nearly so (1*c*). The "rift," or "grain," is vertical, coincides with the linear stretching, and is easily to be obtained. The "hard-way" runs at right angles to the stretching and the "rift" and "lift," but parallel to the crossing joints and the dikes. Compare figure 2.

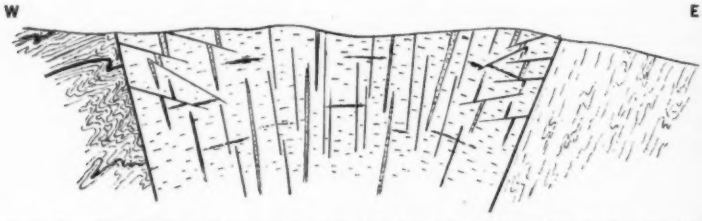

FIGURE 2.—*Generalized Section suggesting the structural Characters of the Strehlen Granite*

The stretching, shown by short broken lines, pitches eastward on the east and westward on the west, while it lies horizontal in the middle. The dikes and joints arrange themselves at right angles to the stretching, forming a symmetric fan. The three paving blocks (figure 1) are drawn as if they were cut out of the section—that is, with their natural dip and orientation. 1*a* represents the Gorkau block (western slope); *b*, the one from Steinkirche (apical zone); *c*, the eastern quarries at Strehlen. Note the arrangement and manner of displacements along the marginal "Streckflächen."

From these facts it is evident that the stretching is a primary flow structure, due to the differential movement of the magma. No later metamorphism can turn a xenolith within a solid granite without producing new cataclastic phenomena, nor can it give rise to flow-bands of different materials. The only reasonable explanation is that the magma

[3] The original bedding planes of the sedimentary inclusions, however, may be orientated in any direction (figure 3).

was flowing in one certain direction, and inclusions with a longer axis were turned until they settled to the most favorable orientation (that is, with the longest axis parallel to the general flow). The contrasted portions within the magma were evidently elongated, stretched, and thinned into the present flow-bands.

One might expect that the strike of the stretching within a granite massive changes from one to the next exposure, so that all conceivable directions are to be met with; yet that is not the case. Within a given massive the strike of the stretching changes but very little, although a

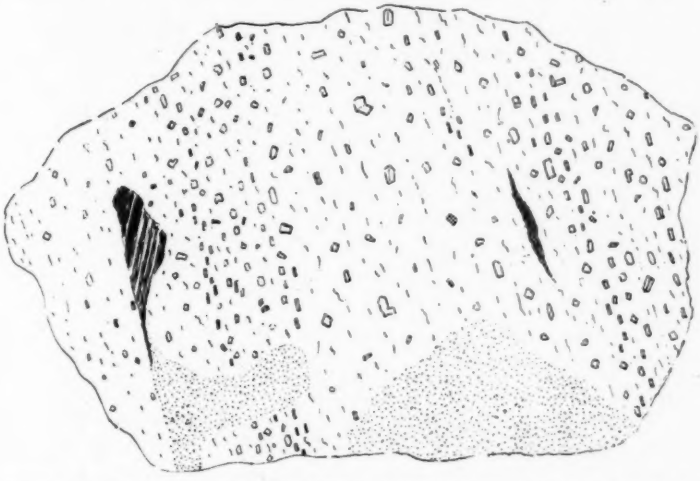

FIGURE 3.—*Primary parallel Arrangement of the Minerals and Inclusions in a porphyritic Granite*

The locality is Nichols Ledge, Woodbury, Vermont. Note the angle between the bedding and the longest axes of the inclusions.

few exceptions are cited below. Convectional currents seem to be almost lacking. Even next to the contact lines the parallelism does not change its strike notably. It can be shown that such phenomena are impossible without the actual cooperation of tectonic, non-magmatic forces which make the magma yield to their stresses. Thus, a north-and-south pressure would cause an east-westward yielding and stretching, as at Strehlen, Silesia; an east-and-west pressure would produce a north-south striking parallelism of the minerals, as at Bethel, Vermont (figure 4). By measuring the strike of the stretching, therefore, we have likewise the direction of tectonic pressure during the time of intrusion.

FIGURE 4.—*Sketch of an abandoned Quarry, Christian Hill, Bethel, Vermont*

Stretching shown by short, broken lines; pitches 12-25 degrees north. Cross-joints shown by long, straight lines; dip, 63-85 degrees south. So do acidic dikes (double lines), aplites (apl.), pegmatites (pe), and quartz veins (SiO_2). "Hard-way" (h.-w.) runs e-w; the "grain" (*g*) runs n-s. "AN" = astronomic work.

It may be said that, so far, all granites surveyed by the Breslau School show the existence of a linear stretching. Its intensity, however, varies in different massives from vigorously stretched to almost massive rocks. The size and the condition of the magma during the intrusion and the relative strength of magmatic and orogenic forces seem to be responsible (see H. Cloos, 14).

Measurements in Germany showed that the stretching does not lie horizontally everywhere. It may pitch.

In most of the German massives, the stretching forms widely bent bow and archlike structures, the strike being the same notwithstanding. Especially near the contact zones, flat-lying flow-lines may plunge slightly and grade into marginal zones of more pronounced pitch. From simple combinations of the strike and pitch of the stretching to the circumference of the massive, there are many gradations to more complicated relations (figures 2 and 6).

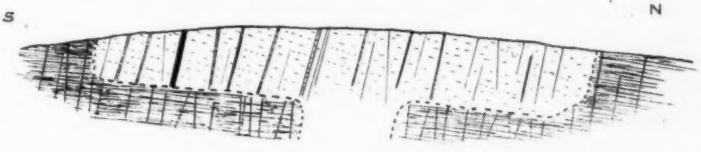

FIGURE 5.—*Cross-section through the Granite of Bethel, Vermont*

An example of one-sided pitch in the stretching of a body whose structures coincide with the older structure of its wall rock. The stretching in both rocks strikes north-south; pitches 10-25 degrees north. Cross-joints dip 85-60 degrees south. Aplites and a lamprophyre follow these cross-joints. The contacts of the intrusive are also probably governed by the structural planes of the wall rock, but the contacts are concealed.

The pitch may be in one direction in the whole region (Baveno, Italy; Bethel, Vermont (figure 4)), or the strike may change, too (Lausitz, Friedeberg, Silesia).

From the foregoing we see that granitic magmas, after entering the crust, rise, and while rising are affected by tectonic forces, as indicated by the uniform strike of the linear parallelism in the whole region. The rising is to be deduced from the formation of broad arches and domes of this parallel structure, the apical zones of which indicate evidently zones of maximum intrusive intensity.

What happened afterwards, when the magma cooled and solidified? Under any conditions we would expect a different behavior on the part of the granitic rock from that of the granitic magma. The quarries of Strehlen (figures 1 and 2) show the following interesting relations (see 5, map, page 17): Whereas the stretching pitches 10-20 degrees to the

east (strike about east-west), there are many hundreds of long, straight joints (German "Querklüfte," "Q"), striking north-south, which dip to the west under an angle (70-80 degrees) which is complementary to the eastward pitch (10-20 degrees) of the stretching. Numbers of acid dikes (aplites, pegmatites, quartz veins) coincide in strike and dip with these joints. Going westward, one crosses the apical zone of horizontal stretching and is faced by the fact that the same north-south striking joints and dikes stand vertically (at Steinkirche). Going still farther, the stretching pitches down to the west, and extensive quarries at Gorkau show that the crossing joints now dip to the east, here, too, complementary to the pitch of the linear structure. The dikes follow the joints in the same manner.

Hence it follows that the crossing joints depend, evidently, for their strike and dip on the orientation of the stretching. Their change in dip in strict correspondence with the changing pitch of the stretching would otherwise be wholly obscure. They converge toward a zone below the axis of the massive and are arranged in a great fanlike system; or, if we consider a vertical east-west section, the bending flow-lines in it will be concentric, circular arcs. The joints and dikes then arrange themselves like radii.

Apparently the joints are very old. They are older than the aplites which follow them. The acid offshoots found their easiest upward way by following these joint faces, pushing the walls aside. Under the north-south pressure, joints and cracks of east-western strike will naturally be closed and compressed at once. Aplitic juice was hardly able to intrude on joint-planes in this direction, but the stress can not close joints which strike parallel to itself. North-south joints may gape as real tension joints without any interference. Besides, the gaping of the faces produces further expansion of the whole rock mass along an east and west direction—an expansion which is a logical result of the yielding of the flowing magma. The crossing joints, therefore, continue the plastic flow and the yielding of the magma when it has become brittle. Evidently the aplites found their entrance easiest on these joint-planes, which opened readily. How closely the plastic stretching and the formations of joints are connected with each other is shown by their constant, mutual orientation (*8a*, page 101; also 14).

Dikes and joints, from this relation, become essential guidelines for the determination of tectonic pressure, both in igneous and sedimentary rocks. Their strike indicates in many cases the direction of stresses; their dip may justify conclusions to the doming of igneous masses (14); and we can, therefore, actually correlate flow structures and plastic phenomena with features of the tectonic zone of fracture.

The outlined combination between the stretching and crossing joints is to be found also in metamorphic rocks. A linear stretching in mica schists and gneisses is one of the most common phenomena, and long ago crossing joints were reported which cut this structure at right angles (Grubenmann, 18, page 110). The mechanics of movement of igneous masses and crystalline schists, therefore, though entirely different, correspond in the mutual coordination of these structures. On the other hand, the same arrangement occurs in many folded but unmetamorphosed rocks, in so far as the axes of the folds represent the lines of yielding to which the crossing joints and dikes have the same relationship as to the stretching. We are able now to compare the direction of the older pressure within the country rock, as indicated by the axes of the folds or the stretching, which seem to coincide generally, with the later pressure

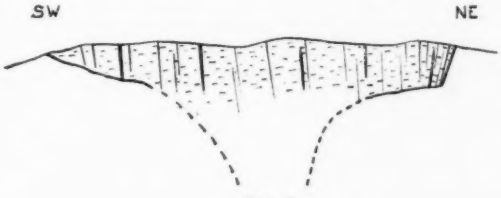

FIG. 6

FIG. 7

FIGURE 6.—*Longitudinal Section through an unsymmetrical Dome*

The locality is Barclay and Jones quarry, Barre, Vermont. The apex of the stretching lies in the northeastern corner; dikes and joints are seen, respecting this arrangement.

FIGURE 7.—*The same intrusive in a Section at right Angles to that shown in Figure 6*

Shows slight platy foliation next to the contacts, the arrangement of an inclusion, and the "Streckflächen."

during the time of an igneous intrusion, and one sees easily how many different possibilities may arise.

During recent years Professor Cloos has published several papers (6*a*, Nr. VI, 7, 8) which give a finer and more detailed conception of magmatic movements. He has succeeded in identifying a system of joints which exhibit displacements of a very interesting kind. The so-called "Streckflächen" (stretching planes), which are likely the oldest formed joints in igneous rocks, occur most frequently in the contact zones. They strike parallel to the curving contacts and usually have a low dip toward the center of the massive (figures 6 and 7), but the striæ on them strike everywhere parallel to the stretching. The displacements are always normal faults, so that the lower blocks have been pushed away from the central part of the massive in the direction of stretching (compare

Cloos, 7, figure, page 9). This is, therefore, another evidence of movement in one and the same direction, but in a different form (first, plastic yielding; later, a separation along crossing joints and dikes, diagonal joints and other planes). By these movements along the Streckflächen the massive has increased in width and its previous upper periphery has been flattened and widened. The whole mass of rock shows an expansion in *one* directiion, obviously a most interesting combination of magmatic and orogenic forces, the latter restricting and governing the directions in which the magma may expand.

The mechanics of the magmatic movement along the contact walls take on a new and interesting light from the following observations (H. Cloos, 14): Along the contact line, dikes and joints appear dipping into the massive, away from the wall rock, but in strike nearly parallel to it. It has been mentioned previously that the linear parallelism near the contact tends to bend conformably to the strike and dip of the contact. The dikes and joints which cross the parallelism (which is the direction of yielding) appear, therefore, as tension joints. In a vertical section across the contact plane, they arrange themselves just as the marginal tension joints in a glacier. In both cases a highly viscous mass is flowing in one direction between solid, stationary walls. Along the walls the mass is dragged and retarded, whereas it moves quickest in the central part. The flow-lines, consequently, are arranged like bows, with the apexes on the top of the tongue of ice forming the glacier and correspondingly in the center of the tongue of magma forming the massive. The tensions between the flowing mass and the resistant walls are emphasized by the characteristically symmetrical arrangement of the tension joints. In the case of the granite it is especially interesting to see that the bulk of the acid dikes follows them.

The same relations between the contact and the marginal tension joints and dikes are exhibited by the granite of Barre, Vermont, which was visited by the writer in 1924 (figure 7).

The Continuation in Depth

In general

The systematic measuring of the outlined structures makes the study of igneous rocks very interesting, which otherwise is often monotonous. It is of special interest to discover that we may learn from the structures at the surface the way in which the intrusive continues downward. The mere fact that a primary parallelism in one direction may prevail in a massive, for instance, makes the assumption of a batholithic origin very

difficult. The prevalence, also, of a few systems of primary joints in certain characteristic directions can not be expected in a batholith. It is interesting, therefore, that Cloos was able to separate certain zones, where the magma most probably entered the crust, from other areas which do not afford any evidence of indefinite downward continuation of the magma.

EXAMPLES

The granite massive of Hauzenberg, Bavaria (8*b*, 10, 15) has a circular ground plan and the contact cuts the structure of the wall rock unconformably; yet the southern part lies almost horizontally on steeply tilted gneisses and amphibolites. In this case the under surface itself is exposed for more than a mile from the contact toward the center of the massive. The northern part, however, no doubt extends downward into the abyssal zone. Previous to the discovery of the under surface it had been determined from the study of the internal structure that it was highly probable that the southern part did not continue downward very far. As a whole, this massive has the shape of a flat-lying tongue, with the root in the northeastern margin. It lies, however, quite unconformably within steeply tilted gneisses, so that it is not to be called a laccolith (10, figure, page 25).

The granite of the Riesengebirge (14) is characterized by platy flow bands which in places are so perfectly developed as to give the rock a stratified appearance. These "layers" of granite form a long, apical zone, which, however, does not lie in the central parts of the massive. On the contrary, the zone in which the flow layers culminate follows closely one side of the contact. Toward the massive the flow layers dip gently, forming a great primary slope, whereas they dip abruptly toward the contact in a narrow zone. From this and several additional features, it is almost certain that the magma rose from beneath this eccentric, apical zone, and that at the opposite side the granite will not continue to a profound depth.

Similar conditions are represented by the largest German massive, the Lausitz granite (6*b*, Nr. I); also by the Brocken granite (Harz Mountains), (10), by the granite of Baveno, Italy, in part (8*c*), and by many others. Space is too short to warrant a detailed report on the evidence which led to the conclusions in every single case.

The surprising shape of these "pseudobatholiths," their location in the crust, and the orientation of their abyssal zones are explained in some cases by the condition and structure of the wall rock. The granite of Striegau, Silesia, has been intruded on the boundary between a series of green schists and a Precambrian gneiss (10). The same position be-

tween gneisses and schists is indicated by the granite of the Riesengebirge (14); the Lausitz massive; the massive of Strehlen and Friedeberg, Silesia (6*b*); the granite of Baveno, Italy (8*c*); of the Erzgebirge and by many others (10). It could be shown in these cases that the gneissic rocks form the resistant floor of hard material which is more or less overlain by the magma and which has not been altered or disturbed by the intrusion. The boundary between gneisses and schists represents obviously a favored plane of expansion for these intrusions.

Another type of favorable plane is represented, however, by zones of weakness in the crust, by far-reaching fault-lines, overthrusts, and trenches.

The Lausitz granite rises along an important disturbance ("Lausitzer Überschiebung"); the Brocken granite has been intruded also into a long fault-line ("Harzrandspalte"), from which it has opened. Numbers of Bavarian granites originated from the famous "Pfahl" line; the granite of Friedeberg appears on the intersection of two important fault-lines. Similar zones of weakness are flexures, zones of general bending of the strike of sediments. The phacolithic type of igneous bodies belongs to this group. Similar relations are represented by the syenite of Glatz-Reichenstein, Silesia (5, 6*a*, Nr. III). The writer found closely corresponding intrusions in the granitic area of Woodbury, Vermont.

From the foregoing it is obvious that certain granitic intrusions play a more dependent rôle within the earth's crust than we have been accustomed to think. We see the magma, in the European examples, subject to the physical characters of the older rocks; it avoids especially the brittle, gneissic areas; it appears around their boundaries and lifts the weaker sediments from the solid basement. The granite apparently finds its easiest way by penetrating along such zones of weakness and by pushing the flexible rocks aside, rather than by melting the overlying crust. In many cases it seems to be the orientation and position of the boundary line of these older blocks which govern, so to speak, the shape of the massives.

These intrusions, which exhibit such a peculiar shape and dependence on the physical condition of the crust, are, however, very small compared with the North American batholiths; and the question rises whether there are any gradations between these two different types of intrusions. Has the huge mass of magma in the American batholiths perhaps overpowered the crust, which, nevertheless, could resist smaller offshoots? The writer has not seen the great American batholiths and has, therefore, no opinion of his own about them. It seems to him, however, a matter of great interest to investigate some of these masses from the

viewpoint and by the methods of Professor Cloos. So much may be said with reasonable certainty about the German intrusions[4] that their history is widely different from that of batholiths, though at first sight they resemble batholiths closely. We may consider them merely as smaller offshoots from a large subjacent mass; but the latter is concealed entirely from any direct observation and its extent and shape can be only a matter of theoretical speculation. All visible intrusions seem to be subjected to tectonic forces of the zone above the batholiths. The writer therefore considers it prudent not to apply the term "batholith" too generally, and to exclude intrusions whose shapes may have resulted from orogenic forces or may have adapted themselves to older structural conditions.

During the summer of 1924 the writer investigated several granite areas of New England. He found the granites of Barre and Woodbury, Vermont, to consist of numbers of small intrusives instead of rather extensive ones, as assumed in previous papers. The granite of Barre, moreover, is seen in places overlying steeply tilted phyllites (figures 6 and 7), and the granites of Woodbury occur repeatedly in strict dependence upon the structure of the country rock.

Some interesting contributions of the investigations of Professor Cloos to the problem of differentiation of magmas may be mentioned very briefly.

Observations in the granitic rocks north of Passau, Bavaria (8, 10, 15), showed that the intrusive series starts with quartz-mica diorites. They appear as small, unconformable lenses and sheets in steeply tilted gneisses, which dip altogether to the north-northeast. Basic granites follow them immediately. Every diorite body is intricately penetrated by the younger rock in the form of curved and picturesque veins. The contact lines are characteristically indistinct. The syenite granite contains numbers of spheroids of diorite which grade into diorite with a kind of pillow structure, the basic granite filling the interstices. All observations point to the conclusion that the diorite was not yet solidified when the more acid rock was intruded. The latter, however, is quite independent of its forerunner. It appears also in completely homogeneous bodies far away from the diorite. Still younger is a normal granite which cuts and has inclusions of both older rocks. This granite

[4] It may be stated again that the gneissic granites (group 1 of the above classification) are out of consideration in this paper. The report deals only with unconformable ("discordant," Daly) massive granites. The question of the continuation in depth of the conformable, gneissic granites is a different matter and is not discussed here. They certainly represent a deeper "niveau" than many genuine granites. Many of them cover extensive areas. Their structure, however, makes it probable that folding movements have been active during their intrusion (4).

penetrates also the diorite bodies as well as the syenite granite, but cuts both rocks on sharp lines. All bodies dip to the north-northeast. The older intrusions offered evidently the best passage for the younger ones, which in turn have overtaken the forerunners. The syenite granite reaches farther to the south-southwest than the diorite; the normal granite still farther, and constitutes more and larger bodies than the older rocks. The internal structure changes from highly schistose and stretched rocks (diorite), through slightly schistose and well stretched (syenite granite), to non-schistose but uniformly stretched rocks (normal granite). Soon after, closely corresponding relations were found in the granite of the Fichtelgebirge and in the massive of Strehlen-Friedeberg, where ball-shaped bodies of an acid diorite occur as inclusions in the midst of the granite. Similar relations are to be seen in some granites of the Odenwald.[5] The writer found large bodies of a basic granite within the light granites of Barre and Woodbury, Vermont ("Dark Barre," "Dark Woodbury"), which were in all places somewhat older than the normal granite and probably were not yet wholly solidified when caught up.

The results from the detailed observations make it highly probable that the differentiation resulted merely as a consequence of, and during, the movement of the magma. Similar observations were lately made in the granite of the Riesengebirge (14) and in the Cortlandt norite north of New York.

Economic Consequences

It seems that some of the results of Doctor Cloos' methods are of considerable economic value. So far as they give information about the origin and the direction of dikes, they are applicable, to a certain extent, to ore-bearing dikes and veins. It is well known that ore-bearing veins prefer certain directions; that with a different direction the filling may change also. The methods outlined enable us to fix a given system of dikes within the internal structure of an intrusive mass and to predict, in cases, changes in strike, dip, and spacing.

An example of ore enrichment along primary structural planes is the Saxonian tin-bearing granites. The working of these granites is now abandoned. The ore, according to maps of the underground workings, occurred in flat seams, which represent a primary direction ("Lager," 5, 14), such as is of great importance in many granite massives, but could not be dealt with in detail in this report. Many of the ore-bearing veins of the Harz Mountains follow the northwest direction, which is the

[5] Communication from H. Scholtz to H. Cloos.

trend of the crossing joints of the associated Brocken granite. Uranium-bearing veins occur in characteristic places around the granite of the Riesengebirge; also uranium-bearing veneers on crossing joints in the granite of Hauzenberg.

In the case of early formed ore-bearing veins, therefore, the methods enable us to direct our special attention from the beginning to certain zones within the intrusive rocks, especially the abyssal zones, and also to certain directions, especially the trend of the crossing joints. Later veins, of course, may be looked for in several additional directions, as, for instance, parallel to longitudinal joints.

The possibility, however, of pseudo-batholithic massives with a rather limited thickness offers a quite different economic problem. If the country rock continues under the granite, we may expect also that certain valuable mineral deposits (coal, iron, zinc, lead, etcetera), so far as they are associated with the older country rock, may continue beneath the later granite, and if the thickness of the granite is not too great it might be possible to operate them. Difficulties in proving the connection between parts outside and those underneath the massive are to be expected, of course, but the mere possibility of tracing older mineral deposits under granite deserves naturally serious scientific and commercial attention. The actual value of this discovery is proved by the graphite mines of Passau, Bavaria. A large part of them are based on material within Precambrian gneisses under a flat, unconformable sheet of granite. The shafts have to be sunk through something like 100 feet of granite, and meet the graphite underneath in straight continuations of the exposures outside the granite on the surface.

The methods described make possible a good many essential and useful conclusions about the mechanics of the intrusion of igneous masses, but the data are to be obtained only by exceedingly detailed and careful field-work. Experience has shown repeatedly that every massive has its peculiarities—its original character. If every characteristic feature of the rock is not followed, so to speak, from exposure to exposure, or if one tries to reach the conclusions only from a few scattered observations, disappointments and erroneous conclusions are certain to result.

Discussion

Prof. James F. Kemp: Doctor Balk's presentation of the new methods for the study of batholiths of granite, as developed by his old teacher, Professor Cloos, of Breslau, brings before us many suggestive points which may lead to new conclusions regarding individual bodies. By plotting the flow-lines, schlieren, joints, and dikes, concentric curves can

be drawn indicating the directions of movement. They resemble our contours in an oil structure and conduct the observer back to an area of massive character and more coarsely crystalline texture which lies over the vent up through which the granite magma has risen from the depths and from which it has spread laterally as a huge sill or laccolith. Beneath these peripheral portions the granite can not go down to profound depths, as the batholiths we have customarily imagined, but must be of much more moderate thickness. Thus, quite a new conception of many granite masses may result, with some important further inferences.

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